A N N U A L   R E P O R T

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TITLE: PREDICTING HYDRAULIC CHARACTERISTICS OF CRITICAL-DEPTH FLUMES OF SIMPLE AND COMPLEX CROSS-SECTIONAL SHAPES

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

Broad-crested weirs, which are hydraulically related to long-throated flumes, are continuing to be well suited to irrigation canal applications. The flexibility in size, liberal construction tolerences, and low head-loss requirements, permit them to be retrofitted to most canal systems and canal shapes. The computer modeling techniques, previously used to develop a series of recommended broad-crested weir sizes for small farm canals, has been extended to larger sizes and to many unlined channel applications.

NEW DESIGNS AND CONSTRUCTIONS:

Major new designs and constructions include the recommendations for broad-crested wiers for circular pipes flowing partly full, rectangular broad-crested weirs primarily for unlined channels, the extension of broad-crested weir sizes up to and including 300 cfs for larger lined trapezoidal shaped canals, and the construction of a series of small portable flumes suited to furrow flows and tailwater monitoring. The circular styles were inspired as part of a cooperative research effort initiated by other federal agencies at Parker, Arizona, and the rectangular versions are a result of efforts to address flow measurement needs for unlined canals.

PARKER STUDY

We are assisting in a cooperative study with the Tribal Council of the Colorado River Indian Tribes (CRIT), the Bureau of Indian Affairs (BIA), the Soil Conservation Service (SCS), and several other organizations. One of the purposes of the project is to increase the amount of land that the tribe can put into production with their current allotment of water. Current sources of waste include deep percolation from irrigated fields and surface drainage, coming mostly from spillage from the off-farm distribution system. The water lost to the project returns to the river and is not lost from the river basin. However, it is lost to the tribe and impairs water quality for downstream users. Our part of the study consists of assisting the SCS with the monitoring of on-farm and off-farm water use.

For the on-farm part of the project, the BIA installed 20 broad-crested weirs of style FB2 from our Farmers' Bulletin, Number 2268. These were precast versions designed and built by Wendell Goodman of the BIA. These flumes are monitored with chart recorders. The charts are read and analyzed by our computer facilities. Considerable fluctuations in discharge were noted for some of the flumes, while for others the discharges were nearly constant. We plan to study this behavior to determine the possible causes for fluctuations.

For the off-farm systems, the BIA is in the process of installing 30 flumes of different styles on the surface drainage network. A majority of these represent direct spills from the canal systems. These include 15 V-shaped flumes of the style used by Replogle in a Florida watershed, 8 broad-crested weirs in free flowing pipes, 3 sharp-crested weirs, and 3 rectangular and 1 trapezoidal broad-crested weirs. These flumes and weirs will also be monitored with chart recorders. We will be processing this data as well.

We encountered many construction problems with these flumes. The flumes, for the most part, were constructed by inexperienced crews. Thus often times, the design dimensions and the constructed dimensions varied considerably. The designed and constructed (as built) side slopes for the V-shaped flumes (triangular broad-crested weirs) are given in Table 1. The side slopes were estimated from a specially made adjustable templet. Another problem was inadequate erosion protection and lack of cutoff walls. Also, the stilling well taps through the canal walls were too low and will tend to silt up. In retrospect, all of these problems could have been alleviated by better construction drawings and the availability of trained supervision. The design for the downstream side of the structure was rather poor in terms of erosion control, the location of the stilling well tap was not well defined and more dimensions could have been given to simplify the side slope layout.

Similar problems were noted with the installation of flumes in pipes. The biggest problem was that of specifying sill height rather than sill width. While the sill height is important for design, the calibration is more sensitive to sill width. Minor changes in sill height only affect the pipe capacity for free-flowing conditions. Since we are artificially constricting the pipe inlet, the capacity should not be a problem. From the drawings, it was not clear that the sill height was referenced to the pipe invert. For corrugated metal pipe (CMP), locating the invert (or sill width) is a problem. The furthest inside edge (toward center of pipe) of the corrugation should be used. Warped pipes may cause difficulties; however, this did not appear to be a problem. For concrete pipe this should not be a problem. The design and constructed dimensions of the pipe flumes is given in Table 2. The flume at site #58 was replaced with a V-flume in the channel downstream. The problem here was that the pipe is too steep and the approach velocity is supercritical. We observed that it did not operate as a flume. From Table 2, we see that it was 1.25 inches too low. A higher sill would have helped. Another problem was that the ramp was too flat. The workmen followed the dimensioned length given in the drawings rather than following a 3:1 slope. Thus there was little break between the pipe, the ramp, and the sill.

Several other flumes were designed and installed as described in Table 3. These present no special calibration problem, however, many of these were fit into extremely complex sites.

This monitoring effort will extend through the end of 1981. The status of this phase of the project after that is not known.

Flumes in Pipes

The work with the SCS and BIA in Parker, Arizona prompted efforts at developing broad-crested weirs for use in free-flowing circular conduits. The flow conditions for these flumes must be the same as that for flumes in open channels. To insure this, the pipe must be free-flowing (not flowing full) and cannot have too much downstream water depth. To accommodate the first requirement the inlet of the pipe is restricted to limit the flow into the pipe. The second requirement may depend on many conditions, so to simplify matters, the flumes were placed at the outlet end of the pipes with a free outfall.

Because of the wide variety of pipe diameters and flow conditions, an attempt was made to use dimensional analysis to reduce the number of variables involved. First, all the flume dimensions were related to the pipe diameter, D (see Fig. 1). For a given pipe diameter, three sill heights were used, namely D/3, D/4 and D/5. The computer model for flume calibrations was run for eleven pipe diameters ranging from 1 to 8 feet. Froude modeling techniques were employed to relate the stage-discharge relationships for the different pipe diameters. The equation used to fit the simulation data was

$$\frac{Q}{D^{5/2}} = a\left(\frac{h_1}{D} + \Delta\right)^b$$

where Q is the discharge, h_1 is the upstream sill referenced depth and a, b and Δ are constants. The results are given in Table 4. These equations were found from best fit functions for the data which ranged from h_1/L = 0.05 to 0.5. The differences between the simulation values and equation computed values was less than 2%. The higher errors generally occurred at low discharges. For a majority of the range, errors are on the order of ± 0.5%. This has a precision higher than the accuracy of the simulation model.

It was a little surprising that the flumes were nearly identical Froude models. We expected some differences due to changes in friction. However, for relatively smooth surfaces (i.e., hand trowelled concrete), roughness changes have little effect on discharge.

There were some inconsistancies in the analysis that were a little surprising. These may have been related to the ranges of values for h_1 (in terms of h_1/L) that were used. It appeared that the data actually fit better to a function of the form

$$\frac{Q}{D^{5/2}} = a\left(\frac{h_1+\Delta_1}{D} + \Delta_2\right)^b$$

which may partially account for changes in relative roughness, since Δ_1 had nearly the same value for all three sill heights.

The maximum discharge that the flume can handle and still remain free-flowing is much less than the discharge that can enter the pipe under orifice control conditions at the pipe entrance. The general equation for the discharge through an orifice is

$$Q = C_d A \sqrt{2gh}$$

where C_d is a constant (approximately 0.62), A is the cross-sectional area of the opening, g is the acceleration due to gravity, and h is the head on the orifice measured from the center of area A. Since for a circular opening, $A = \pi D^2/4$, this can be expressed as

$$\frac{Q}{D^{5/2}} = C_d \frac{\pi}{4} \sqrt{2gh/D}$$

Thus for a given ratio of head to pipe diameter, Q is related to $D^{5/2}$ directly. For D = h, we get $Q = 3.91 D^{2.5}$. From Table 4, we see that for the three flume sizes this constant is 2.23, 1.92 and 1.47, respectively. Since Q is directly related to area, the area of the entrance must be reduced to 2.23/3.91, 1.92/3.91 and 1.47/3.91, or 57, 49 and 38% of the original area for the three sill heights. These values, of course, are related to $\sqrt{h/d}$.

The cooperative project with Spain in the Ebro river basin added additional information on semicircular and U-shaped canals. For these conditions, it became obvious that the sill heights chosen for the pipe flumes were not adequate for these channels. Also, recent construction at Parker indicated that perhaps they should be described by sill width. This will be investigated further and a more precise analysis performed to produce some more useful results.

Rectangular Flumes

Most of the work on flumes and broad-crested weirs up to now have dealt with lined irrigation canals and (unlined) natural channels. There is a serious need for measuring structures usable in unlined irrigation canals. We could line a section of the unlined ditch and place a structure in it. Several canal sections and flumes have been put in near Parker, Arizona by this method. However, some of the flume sidewalls have collapsed because large amounts of earth fill was used. With proper construction techniques, this could be avoided, however, it may be more appropriate to have some designs specifically suited to unlined canals. The most logical candidate is a rectangular flume which can be made of concrete, stone, metal, wood or any such material. This will also facilitate the use of local construction materials.

The throat section of the flume is a simple rectangle with dimensions depending on flow situation and site conditions. The approach section could utilize the existing channel, as did the trapezoidal broad-crested weirs. However, this adds additional variables which complicate the problems. For given flume throat dimensions, there are an infinite number of possible approach areas and velocities. These could be approximated and accounted for, however, at the expense of simplicity. For these reasons, we have chosen to use a rectangular approach channel of the same width as the flume throat. Thus the vertical walls for all flume sections are the same and the sections are only delineated by the bottom hump or weir.

It is reasoned that except for the flow very near the flume side wall, the flow over the flume can be equally divided according to width. That is, a 2 m wide flume will deliver very nearly twice as much flow as a 1 m wide flume under the same flow conditions. Thus we may be able to select ranges of flume widths that will give nearly identical values of unit discharge (discharge per unit width).

Two other variables that need to be considered are the sill heights (p_1) and canal depths (d) associated with each range of flume widths (b). Thus there are three ratios which can be looked at: 1) ratio of canal width to depth b/d, 2) ratio of sill height to canal height p_1/d, and 3) ratio of flume throat width to depth, $b/(d-p_1)$. The first relates to conditions which may be expected to exist and to ease of construction. The second relates to the design of the flume in terms of water levels and submergence. The last ratio affects the second and relates to flume submergence and accuracy. Considerable judgement is involved in selecting the ranges of these ratios for different canal widths and sizes. As discussed in an earlier paper for large lined canals, as the canals get larger the width to depth ratios get larger. This is dictated by physical limitations in the construction of deep canals.

A number of simulation runs were made with the flume calibration model for a wide range of canal and flume dimensions. An analysis was performed to determine the errors involved with grouping different flume widths and sill heights. This analysis resulted in a number of flume ratings as given in Table 5. The errors involved are less than ±1% throughout the entire discharge range. Because of these low errors some recombination may be possible, however, for some combinations the errors are multiplicative, not additive, and large errors may be introduced rapidly. The aspect ratios defined above for these flumes in given in Table 6.

Miscellaneous Flumes and Activities

A workshop for Soil Conservation Service employees in Arizona was conducted to check them out on the use of portable flumes that the SCS had constructed. Two sizes were built, one with a 12-inch throat length for 24-inch deep canals and one with an 18-inch throat length for deeper flows in 36-inch deep canals.

Four of the five designs for portable flumes, made by using a 90° trough of sheet metal with an appropriate sill and depth sensing arrangement, were constructed. Only the largest was not built. Minor changes in dimensioning from the initial drawings were made to accommodate standard available sheet-metal sizes and usual machine shop tools. The original designs were presented in Annual Report 1979. Other drawing changes since last year include redesignating dimensions in terms of throat width instead of throat length.

For concrete-lined canals up to 300 cfs, recommendations of standard-sized flumes were presented at the ASCE, Irrigation and Drainage Division Conference, in Boise, Idaho, 23-25 July. These appear in the conference proceedings.

A flume was installed in Sri Lanka using the Boise paper. In a letter from the Consultant to the Sri Lanka authorities, the description of the installation problems was similar to our own experiences with unskilled labor on the Indian Reservation. However, even with the apparent poor conditions, as-built, the Sri Lanka installation is within required performance tolerances for good measurements and further illustrates the construction advantages of this style of critical-flow devices.

Another flume of the sizes presented in the Boise paper was constructed by the Bureau of Indian Affairs (Larry Wilke) near Sacaton, Arizona. He told us that they spent about $300 in materials and local labor installing it. Adequate supervision was available and the installation is very good. A comparable Parshall flume in the other canal branch was bid at $12,000 (as itemized in the total bid package).

Mr. M. G. Bos from the International Institute for Land Reclamation and Improvement/ILRI, the Netherlands, visited our laboratory during part of February and March, and again for five weeks in November and December. During this time, and a month J. A. Replogle spent at ILRI (September), about six of nine chapters for an agricultural handbook on flumes were drafted. Also partly drafted was a book chapter for "Advances in Irrigation" to be edited by Dan Hillel.

Several thousand copies of Farmers Bulletin Number 2268 have been distributed and the demand is still lively.

SUMMARY AND CONCLUSIONS:

Broad-crested weirs, which are hydraulically related to long-throated flumes, are continuing to be well suited to irrigation canal applications. The flexibility in size, liberal construction tolerances, and low head-loss requirements permit them to be retrofitted to most canal systems and canal shapes. The computer modeling techniques, previously used to develop a series of recommended broad-crested weir sizes for small farm canals, has been extended to larger sizes, up to 300 cfs, and to many unlined channel applications.

Major new designs and constructions include the recommendations for broad-crested weir sizes suited to sewer flows, or other circular pipes flowing partly full; rectangular broad-crested weirs, primarily recommended for unlined canals; and a series of small portable flumes suited to furrow flows and tailwater monitoring.

The circular styles were used as part of a cooperative effort with other agencies to monitor the disposition of irrigation diversions and the effect of intensive on-farm practices on this disposition. The rectangular versions are a result of efforts to address flow measurement needs for unlined canals.

Twenty or more flumes in lined canals were installed in the on-farm part of the study near Parker, Arizona, on Indian lands. Thirty more flumes of various styles from triangular to circular were installed at strategic drainage points.

For the rectangular flumes, tables are presented in generalized form in terms of discharge per unit width and as a function of sill height. The effects of narrow weir openings are accounted for by offering different tables for pre-determined ranges of weir width.

REFERENCES:

Replogle, J. A., Clemmens, A. J., and Bell, E. D. 1980. A method and apparatus for measuring rate of flow in channelized flowing bodies of water such as irrigation canals. U.S. Patent 4,195, 519. April 4, 1980.

PERSONNEL: J. A. Replogle, A. J. Clemmens

Table 1. Side Slopes for V-shaped Flumes

Site #	Design Sideslope	Constructed Sideslope	Location
42	3.0	3.3	27R-25
52	3.0	3.5	19L-16
53	3.0	3.0	19L
55	3.0	3.0	27R-4
56	3.0	2.8	27R-20
57	4.0	4.5	27R-23-2
58	3.0	3.0	27R-4-2
60	3.0	2.6	27R-11-24
61	3.0	3.3	27R-11
62	3.0	2.5	27R-25
64	3.0	3.1	27R
66	3.0	3.5	19R-37
74	3.0	3.1	73-25R-15
76	3.0	3.3	73-36-28
78	3.0	3.4	73-36-34
82	4.0	4.5	90-Tyson Wash

Table 2. Sill Width for Pipe Flumes

Site #	Pipe Diameter	Design Sill Height	Design Sill Width	Constructed Sill Width	Computed Sill Height	Location
	(inches)	(inches)	(inches)	(inches)	(inches)	
54*	30 concrete	6.0	24.0	23.75	5.84	27L
(58)**	36 concrete	7.2	28.8	26.75	5.95	27R-4-2
68	30 concrete	6.0	24.0	23.25	5.52	73-25R-13
69	24 metal	4.8	19.2	20.75	5.97	73-25R-3
71*	36 concrete***	7.2(6.0)	28.8(24.0)	26.25	5.68	73-36-7
72	30 CMP****	6.0	24.0	24.75	6.52	73-36-7-1
73	36 concrete	7.2	28.8	30	8.05	73-36
75	24 CMP	4.8	19.2	19.75	4.83	73-36-20
77	24 CMP	4.8	19.2	18.75	4.51	73-25R

* These flumes are not operating satisfactorily and need to be modified.

** This flume was replaced with a V-flume in the channel downstream.

*** This pipe was shown as a 30-inch pipe in the drawings resulting in too low of a sill.

**** Corrugated metal pipe.

Table 3. Other Measuring Devices Installed.

Site #	Flume Style	Comments or dimensions	Location
51	Rectangular BCW*	Sheet metal flume on concrete wall not yet constructed	Tunnel wasteway
63	Rectangular sharp-crested weir	Approach section built (4.5' wide, 2.0' high) weir plate installed	27R-36
67	Trapezoidal BCW	Flume FB2 installed in existing concrete-lined ditch	79
70	Two rectangular sharp-crested weirs	Approach sections built (2 at 2.0' wide, 25' high) weir plate installed	73-25R
79	Rectangular sharp-crested weir	Weir in drop box not started (6.0' wide, 3.5' high)	90
80	Rectangular BCW	Rectangular flume in drop box $b = 4'$, $x_L = 2'$, $X_b = 4'$, $x_a = 0'$, $p_1 = 2'$	90-56
81	Rectangular BCW	Rectangular flume in trapezoidal chute $b_1 = 3'$, $z_1 \approx 1:1$, $b = 3'$, $x_L = 2'9"$, $x_b = 3'$, $p_1 = 1' \pm$	90-56

* Broad-crested weir.

Table 4. Discharge Relationships for Pipe Flumes (Units are in cfs and ft).

Sill Height, P1	Discharge Equation	Maximum Discharge	Minimum Design Head Loss	Maximum Head Loss	Entrance Area Control
D/5	$Q=4.100(Y+0.0055\ D)^{1.742}\ D^{0.758}$	$Q_{max} = 2.23\ D^{2.5}$	0.025 D	0.070 D	$0.57/\sqrt{h/D}$
D/4	$Q=3.937(Y+0.0042\ D)^{1.690}\ D^{0.810}$	$Q_{max} = 1.92\ D^{2.5}$	0.032 D	0.065 D	$0.49/\sqrt{h/D}$
D/3	$Q=3.667(Y+0.0014\ D)^{1.614}\ D^{0.886}$	$Q_{max} = 1.47\ D^{2.5}$	0.049 D	0.057 D	$0.38/\sqrt{h/D}$

Table 5. Unit width discharges in liters per second per meter of width for rectangular broad-crested weirs. Ramp lengths (not tabulated) equals $3p_1$.

$b = 0.1$ to 0.2 m		$b = 0.2$ to 0.3 m		$b = 0.3$ to 0.5 m		
$d = 0.1$ m		$d = 0.3$ m		$d = 0.4$ m		
$L = 0.2$ m		$L = 0.4$ m		$L = 0.5$ m		
$L_a = 0.05$ m		$L_a = 0.1$ m		$L_a = 0.2$ m		
q (l/s/m)	h_1 (m) $p_1 = 0.05$	q (l/s/m)	h_1 (m) $p_1 = 0.1$ m	q (l/s/m)	h_1 (m) $p_1 = 0.1$ m	h_1 (m) 0.2 m
2	0.012	6	0.024	10	0.034	0.034
3	0.015	8	0.029	20	0.052	0.053
4	0.018	10	0.034	30	0.067	0.068
5	0.021	12	0.038	40	0.080	0.082
6	0.024	14	0.041	50	0.093	0.095
7	0.026	16	0.045	60	0.104	0.107
8	0.029	18	0.049	70	0.115	0.118
9	0.031	20	0.052	80	0.125	0.129
10	0.033	25	0.060	90	0.135	0.139
12	0.037	30	0.067	100	0.144	0.149
14	0.041	35	0.074	110	0.153	0.158
16	0.044	40	0.080	120	0.161	0.167
18	0.048	45	0.087	130	0.170	0.176
20	0.051	50	0.093	140	0.178	0.184
22	0.054	55	0.098	150	0.185	0.192
24	0.057	60	0.104	160	0.193	-
26	0.060	65	0.110	170	0.200	
28	0.062	70	0.115	180	0.208	
30	0.065	75	0.120	190	0.215	
35	0.072	80	0.125	200	0.222	
40	0.078	90	0.135	220	0.235	
45	0.084	100	0.144	240	0.248	
50	0.089	110	0.153	260	0.261	
55	0.095	120	0.161	280	0.273	
		130	0.170	300	0.285	
		140	0.178	320	0.296	
		150	0.185			
		160	0.193			
	$\Delta H = 0.011$ m		$\Delta H = 0.022$ m		$\Delta H = 0.025$ m	0.033 m

Table 5. Continued

b = 0.5 to 1.0 m; d = 0.7 m; L = 0.8 m; L_a = 0.3 m

q (l/s/m)	h_1 (m), p_1 = 0.2 m	0.3 m	0.4 m
20	0.053	0.053	0.053
40	0.083	0.083	0.083
60	0.108	0.109	0.109
80	0.129	0.131	0.132
100	0.149	0.151	0.152
120	0.168	0.170	0.171
140	0.185	0.188	0.189
160	0.201	0.204	0.206
180	0.217	0.220	0.222
200	0.231	0.236	0.238
220	0.246	0.250	0.253
240	0.260	0.265	0.267
260	0.273	0.278	0.281
280	0.286	0.292	0.295
300	0.299	0.305	-
320	0.311	0.317	
340	0.323	0.330	
360	0.335	0.342	
380	0.346	0.354	
400	0.357	0.365	
420	0.368	0.377	
440	0.379	0.388	
460	0.390	0.399	
480	0.400	-	
500	0.410		
550	0.435		
600	0.459		
650	0.483		
ΔH =	0.047m or 0.1 h_1	0.058m	0.059m

b = 1.0 to 2.0 m; d = 1.0 m; L = 1.0 m; L_a = 0.3 m

q (l/s/m)	h_1 (m), p_1 = 0.25 m	0.50 m	0.75 m
20	0.054	0.054	0.054
40	0.083	0.084	0.084
60	0.109	0.110	0.110
80	0.131	0.132	0.133
100	0.151	0.153	0.154
120	0.169	0.172	0.173
140	0.187	0.190	0.191
160	0.203	0.207	0.209
180	0.219	0.224	0.225
200	0.234	0.239	0.241
250	0.269	0.276	-
300	0.302	0.311	
350	0.333	0.343	
400	0.362	0.373	
450	0.389	0.402	
500	0.416	0.430	
550	0.441	0.457	
600	0.465	0.483	
650	0.489	-	
700	0.512		
750	0.535		
800	0.556		
850	0.578		
900	0.598		
950	0.619		
1000	0.639		
1100	0.677		
1200	0.714		
ΔH =	0.061m or 0.1 h_1	0.083m	0.068m

b > 2.0 m; d = 1.5 m; L = 1.5 m; L_a = 0.3 m

q (l/s/m)	h_1 (m), p_1 = 0.50 m	0.75m	1.00 m
50	0.098	0.098	0.099
100	0.154	0.155	0.155
150	0.200	0.201	0.202
200	0.240	0.242	0.243
250	0.277	0.280	0.281
300	0.311	0.315	0.316
350	0.344	0.347	0.350
400	0.374	0.379	0.381
450	0.403	0.409	0.411
500	0.431	0.437	0.440
550	0.458	0.465	0.468
600	0.484	0.491	0.495
650	0.509	0.517	-
700	0.533	0.542	
750	0.557	0.567	
800	0.580	0.590	
900	0.625	0.636	
1000	0.667	0.680	
1100	0.708	0.723	
1200	0.748	-	
1300	0.786		
1400	0.823		
1500	0.860		
1600	0.895		
1700	0.929		
1800	0.963		
1900	0.996		
ΔH =	0.107m	0.124m	0.119m

Table 6. Channel and Flume Dimensions and Resulting Aspect Ratios for Rectangular Flumes.

Width range, b	Maximum canal depth,d	Range of sill heights,P	b/d	P/d	b/(d-p)
(m)	(m)	(m)			
0.1	0.1	0.05	0.67	0.33	1.0
0.2-0.3	0.3	0.1	0.67-1.0	0.33	1.0-1.5
0.3-0.5	0.4	0.1-0.2	0.75-1.25	0.25-0.5	1.0-2.5
0.5-1.0	0.7	0.2-0.4	0.71-1.43	0.29-0.57	1.0-3.3
1.0-2.0	1.0	0.25-0.75	1.0-2.0	0.25-0.75	1.33-8.0
2.0-5.0	1.5	0.5-1.0	1.25-3.33	0.33-0.67	2.0-10.0

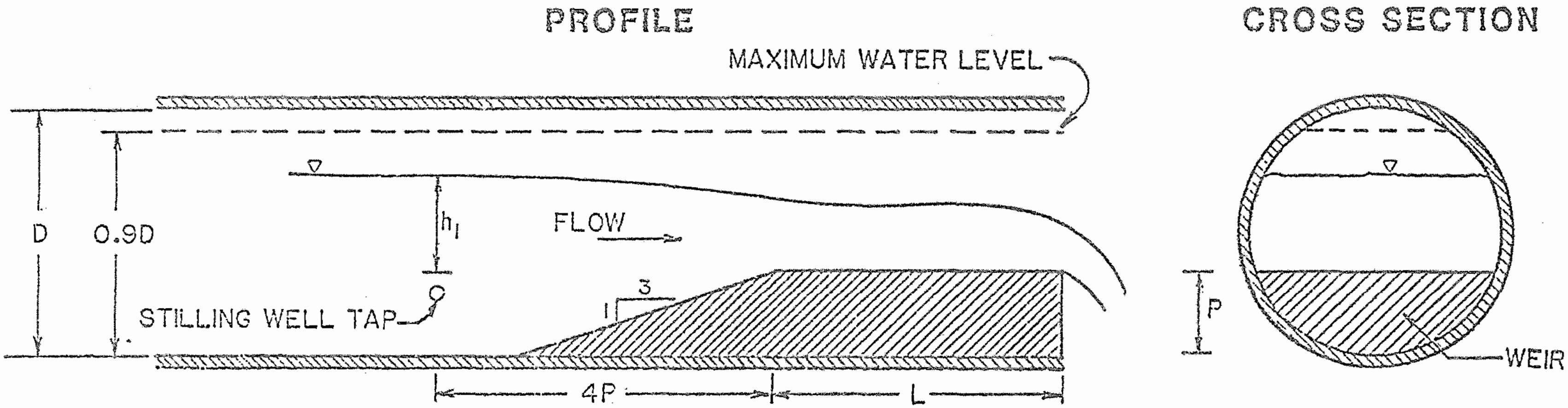

Figure 1. Broad-crested weir in a pipe flowing partly full.

TITLE: MATHEMATICAL MODELING OF BORDER IRRIGATION HYDRAULICS

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

Significant progress has been made over the last several years on the development of mathematical models and their application to border irrigation. The zero-inertia border irrigation model developed by Strelkoff and Katapodes has been continually refined and improved. We have received numerous requests for the model, primarily from university professors and researchers. The model has tremendous potential as both a research and a design tool. Some additional work will be necessary to produce a model that is documented and reliable enough to be useful to those not thoroughly familiar with the model details.

Work has begun on furrow irrigation modeling. Two models were developed at Davis, California, a complete model and a zero-inertia model. These models consist only of the advance phase; however, comparisons with field data show excellent results. An analysis was performed on methods for estimating infiltration in furrows. The results will be published in a Ph.D. dissertation at Davis, California. Further work will be required to extend this work to cover all phases of an irrigation.

Results of Modeling Efforts

A number of results have been produced by the zero-inertia model. These can be categorized as direct results and indirect results. The direct results can be obtained in either dimensional or non-dimensional terms. The results already obtained as well as those being worked on are summarized below.

The direct results for level basins have been primarily in nondimensional terms. These include advance curves, maximum advance distance, recession curves (for field lengths longer than maximum advance distance) and maximum flow depth. Comparisons with the SCS border irrigation handbook produced a variety of results. For flow depths, the SCS solutions ranged from 20% high to 20% low depending upon infiltration. For the design curves in terms of unit flow rate, field length and application efficiency, the SCS solutions were close in many cases. However, for extreme conditions they were usually quite a bit off and their curves had the wrong trend. This prompted further analysis utilizing indirect results.

For sloping borders, solutions have been presented for the advance curve, the maximum advance distance and the subsurface profile in nondimensional terms. In dimensional terms, some comparisons to the SCS border irrigation handbook have been made. The results were somewhat inconclusive since the attainable efficiencies cannot be determined for the SCS design charts. Design charts are being prepared for sloping borders which will include ponded water depths. An analysis of runoff on sloping borders is also being made.

A set of design curves for level basins has been developed which essentially replaces the SCS design curves on level basins. This represents an indirect solution from the model. This solution has several advantages over the SCS design curves. First, it can be used with a much wider range of infiltration conditions. Second, it establishes maximum basin lengths. Problems had been encountered in the field where basins designed from the SCS handbook were too long. In one case, the basins were about twice as long as they should have been.

Work has started on producing similar results for sloping borders. The solutions are more complex due to the addition of an extra variable (slope) and the end conditions (open or blocked end). A detailed discussion on the dimensional analysis for developing these indirect results for sloping borders is being prepared.

Level Basin Evaluation

Methods have been developed for estimating the (water) distribution uniformity in level basins from measurements taken during an irrigation. Two cases are distinguished: 1) infiltration follows a power function; 2) infiltration follows a power function initially and then changes to a constant infiltration rate (branch function). For a power function, a graphical solution was developed for the distribution uniformity, DU, (minimum/average depth infiltrated) in terms of a, h, and t_t/t_n, where a is the exponent for the power infiltration function, h is the exponent for the power advance function, t_t is the advance time and t_n is the minimum infiltration opportunity time. For the branch infiltration function, the solution for DU is found from

$$DU = 1 - \frac{i_f t_t}{z_g(1 + h)}$$

where i_f is the final infiltration rate, z_g is the gross or average depth of water applied and t_t and h are as defined above.

The application efficiency is determined by the management of the system. A good design will yield a high distribution uniformity and will make management easier.

Infiltration Functions

One of the most important considerations in the design and management of surface irrigation systems is infiltration. Infiltration theory, however, has been unable to predict infiltration under actual field conditions. This is due to the complex nature of actual soil systems, spatial variability in soil properties, surface conditions, etc. For this reason, most work of a practical nature in the irrigation field relies on empirical infiltration equations. However, for predicting relative changes in infiltration over the irrigation season, it would be useful to have an infiltration equation with a theoretical base. This is not always practical.

Nine infiltration equations were selected for analysis. Field data from several sources was fit to this data with a curve fit program (Arbitrary Curve Fit) for both cumulative infiltration and infiltration rate versus time. These equations are given in Table 1 where z is the cumulative infiltration depth, t is the infiltration opportunity time, k, a, c, t_f, and t_c are constants, e = 2.18, ln is the natural logarithm and Atan is the arctangent in radians.

The average regression coefficients for these nine functions for 21 sets of ring data taken at a wide variety of sites is given in Table 2. These are listed in the order of highest to lowest total average regression coefficient for both cumulative infiltration and infiltration rate. Also listed are the number of parameters required in the equations. Similar results are obtained for the results of border irrigation studies at two sites as shown in Table 3. These results are not completed and have not been fully analyzed.

It is a common practice in the irrigation hydraulics field to plot infiltration data (both cumulative and rate) on logrithmic axes. A best fit line through the data then give an estimate of the infiltration function in terms of a power function (Kostiakov equation). In effect, this technique is equivalent to minimizing the sum of the squares of the differences between the logrithmic values. This has the effect of weighting the values to obtain a better fit throughout the entire time range. Thus the logrithmic values of the data were used in the curve fit analysis.

In determining which function to use, it is important to analyze the nature of each equation. The Kostiakov equation is a power function. It appears to be a good fit except for low infiltration rate soils at long times which tend toward a constant infiltration rate (for the power function the infiltration rates goes to zero). The Kostiakov branch and modified functions were devised to account for this, but require an additional parameter. The SCS function adds an extra parameter which curves the cumulative infiltration curve in the right direction, but does not change the infiltration rate curve. Thus it adds an additional parameter with little effect. The Horton equation is an exponential equation. It does a poor job of fitting the data, particularly since the infiltration rate at time zero approaches a constant rather than infinity. The Horton modified equation fits the data better, but still has the same fundamental weakness.

The theoretical equations (Philip and Green-Ampt) do a fair job of fitting the data, but not as good as the empirical functions. Even though there is no statistical difference, the other functions continually outrank these for a majority of the data. The Collis-George equation is an attempt to modify the Philip equation to fit the data better. It seems to do an excellent job.

A variety of conclusions can be drawn about this analysis. For use in irrigation studies my recommendations are as follows. The Kostiakov or power function equation can be used with sufficient accuracy for many conditions encountered. It has sufficient accuracy and only contains two parameters. For situations where the infiltration rate maintains a relatively constant value, an additional parameter can be added to the Kostiakov function to form the modified or branch function. I prefer the branch function which has some advantages analytically. If results of a more theoretical nature are desired, a tremendous amount of research is required to relate the coefficients in these equations to physical parameters. Actually measuring these parameters to predict the infiltration for an irrigation is a major problem.

Sloping Border Optimization

Finding optimum designs for sloping irrigation borders is not very straightforward. The major design parameters are slope and field length. Obviously the optimum slope is very much affected by the existing ground slope. For relatively steep slopes, minor changes in slope have very little effect on the design or operation. For mild slopes, these changes can cause major differences. The infiltration rate is a major factor in any irrigation system design. For level basins, a decrease in infiltration magnitude always improves the distribution uniformity. For sloping borders, it can cause either a decrease or an increase in uniformity. The effects of field length will be analyzed at another time.

As an example, an analysis for determining the optimum slope for a mildly sloping ponded border will be made. The situation chosen closely resembles an existing field on the McDonnell-McElhaney farm near Wellton, Arizona. The soil is a Dateland sandy loam. The infiltration rates varied considerably for the two conditions run. The field length was 600 ft. The crop was alfalfa. The zero-inertia model was run to determine the maximum potential efficiency at 100% adequacy for five different slopes and two infiltration functions. Changes in crop conditions (roughness) were not analyzed. The particulars are as follows: Manning n = 0.15, field length = 600 ft., desired depth infiltrated = 3 in., infiltration exponent = 0.6, infiltration magnitude, k = 2 and 3 in/hr^a, and slope = 0.000, 0.025, 0.050, 0.075 and 0.100%. The results are given in Figures 1 and 2.

The curves in Figure 1 show a consistent trend of higher potential efficiencies for steeper slopes for the lower flow rates. For the higher flow rates, the trend begins to reverse. This is easily explained. For the rising portion of these curves (lower flow rates), the upper end of the field is being overirrigated. Near the peak of the curve, both the upper and lower ends are overirrigated, and during the falling portion of the curve, the lower end is being overirrigated. For level basins (slope = 0.0), the upper end is always overirrigated, thus the curve is continually rising. The curves for s = 0.050 and 0.025% peak at much higher flow rates than shown here. Design based on this curve alone would result in a relatively high slope.

The situation is considerably different in Figure 2. The peaks for the higher slopes are at very low flow rates and the efficiencies at the higher flow rates are extremely low. (The flat portion of these curves results from the ponding of water over the field to a level that allows 3 inches to infiltrate at the upper end). There are two ways to approach the design. First, choose a slope that always has a high efficiency and adjust the flow rate over the season. This is currently impractical due to the complexities in determining infiltration and the range in flow rates required. An alternate way is to choose a slope that will give you a reasonable efficiency for a fixed flow rate. For example a slope of 0.050% will yield an efficiency of 75% at a unit flow rate of 0.075 cfs/ft for all conditions. Higher efficiencies can be obtained with moderate changes in flow rate.

SUMMARY AND CONCLUSIONS

The development work on the zero-inertia border irrigation model is nearing completion. A final model should be completed and fully documented by the end of 1981. So far, several different solutions have resulted from the initial versions of the model. These results are presented in graphical form and include: advance, recession and maximum water depths in level basins; advance, maximum advance distance and subsurface profiles for sloping borders; and design aides for level basins. Future results include the design of sloping borders with runoff with and without pumpback system and sloping ponded borders. A furrow model is currently in the development stages, but could be completed as early as 1982.

Other work in surface irrigation related to irrigation modeling has been done. Evaluation techniques for level basins have been developed, which greatly simplify the measurements required. It has been shown that at the present time theoretical infiltration functions have no advantage over empirical functions. Also, a numerical example is given for optimizing the conditions on a sloping border system (with results from the zero-inertia model), which shows the difficulty of designing and managing such systems.

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See Appendix for additional references.

PERSONNEL: A. J. Clemmens, J. A. Replogle, A. R. Dedrick.

Table 1. Infiltration Functions

Function Name	Cumulative Function	Rate Function
Kostiakov	$z = kt^a$	$i = akt^{a-1}$
Kostiakov Branch	$z = kt^a$ $z = k(1-a)t_f{}^a+ct$	$i = akt^{a-1} \quad t \leqslant t_f$ $i = c \quad t \geqslant t_f$
Kostiakov Modified	$z = kt^a+ct$	$i = akt^{a-1}+c$
SCS	$z = kt^a+c$	$i = akt^{a-1}$
Horton	$z = k(1-e^{-at})$	$i = ake^{-at}$
Horton Modified	$z = k(1-e^{-at})+ct$	$i = ake^{-at}+c$
Philip	$z = kt^{1/2}+ct$	$i = \frac{1}{2} kt^{-1/2}+c$
Collis-George	$z = k(\text{Atan } t/t_c)^{1/2}+ct$	$i = \frac{kt_c(\text{Atan } t/t_c)^{-1/2}}{2(t_c{}^2 + t^2)} + c$
Green-Ampt	$t = \frac{1}{k}[z-a\ln\frac{a+z}{a}]$	$i = k\frac{a+z}{z}$

Table 2. Average Regression Coefficients for Ring Data

	Cumulative Data	Rate Data	Total	# of Parameters
Kostiakov Branch	0.8562[a]	0.7421[c]	0.7992	3
Kostiakov Modified	0.8563[a]	0.7408[c]	0.7986	3
Collis-George	0.8584[a]	0.7301[c]	0.7943	3
SCS	0.8563[a]	0.7273[c]	0.7918	3
Kostiakov	0.8553[a]	0.7273[c]	0.7913	2
Horton Modified	0.8342[a]	0.7034[c]	0.7688	3
Philip	0.8273[a]	0.7043[c]	0.7658	2
Green-Ampt	0.8163[a]	0.6925[c]	0.7544	2
Horton	0.7540[b]	0.4344[d]	0.5942	2

a,b,c,d - indicates statistical significance at 5% level

Table 3. Average Regression Coefficients for Border Data

	Cumulative Data	# of Parameters
Kostiakov Branch	0.9600	3
Kostiakov Modified	0.9600	3
Collis-George	0.9595	3
SCS	0.9595	3
Kostiakov	0.9498	2
Philip	0.8348	2
Green-Ampt	0.8066	2

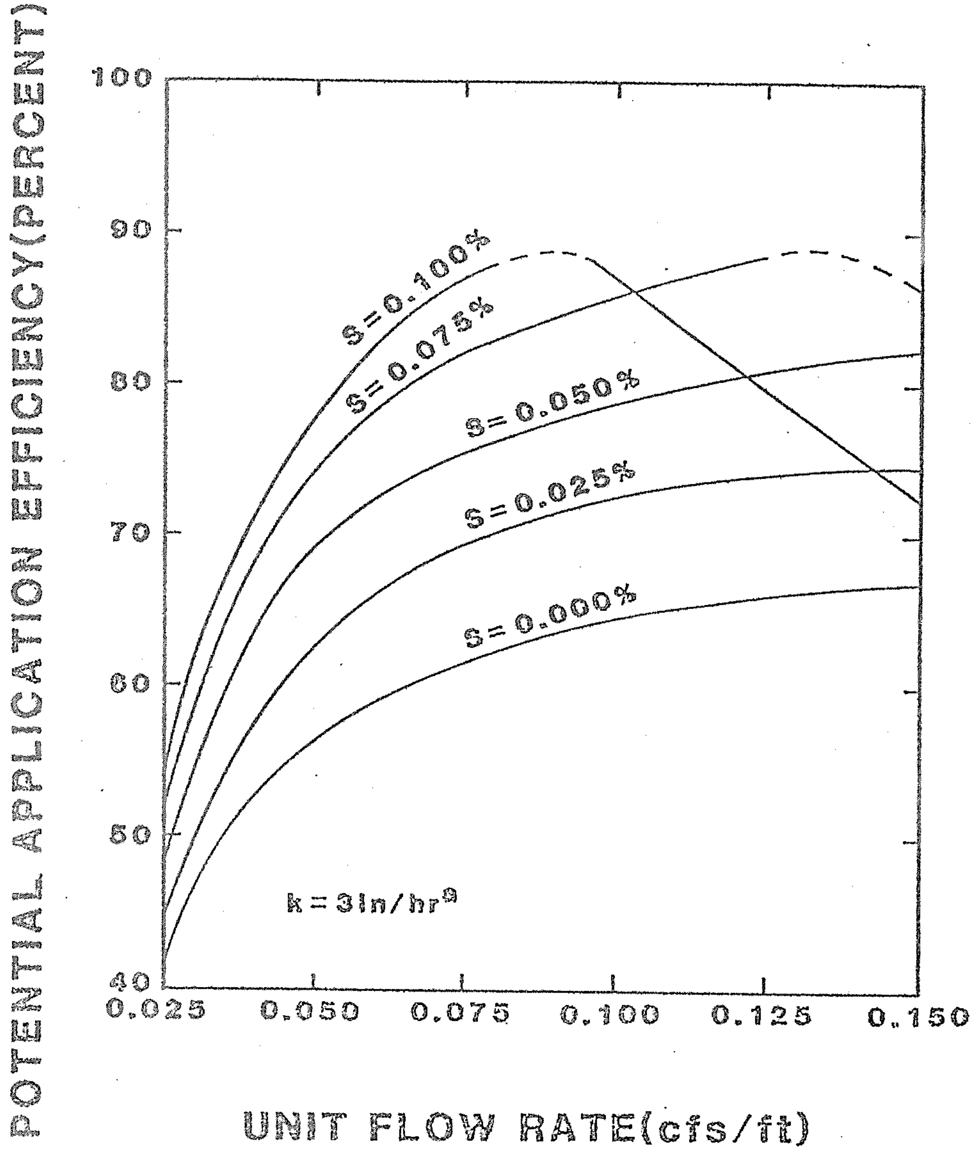

Fig. 1. Potential efficiencies for dry conditions.

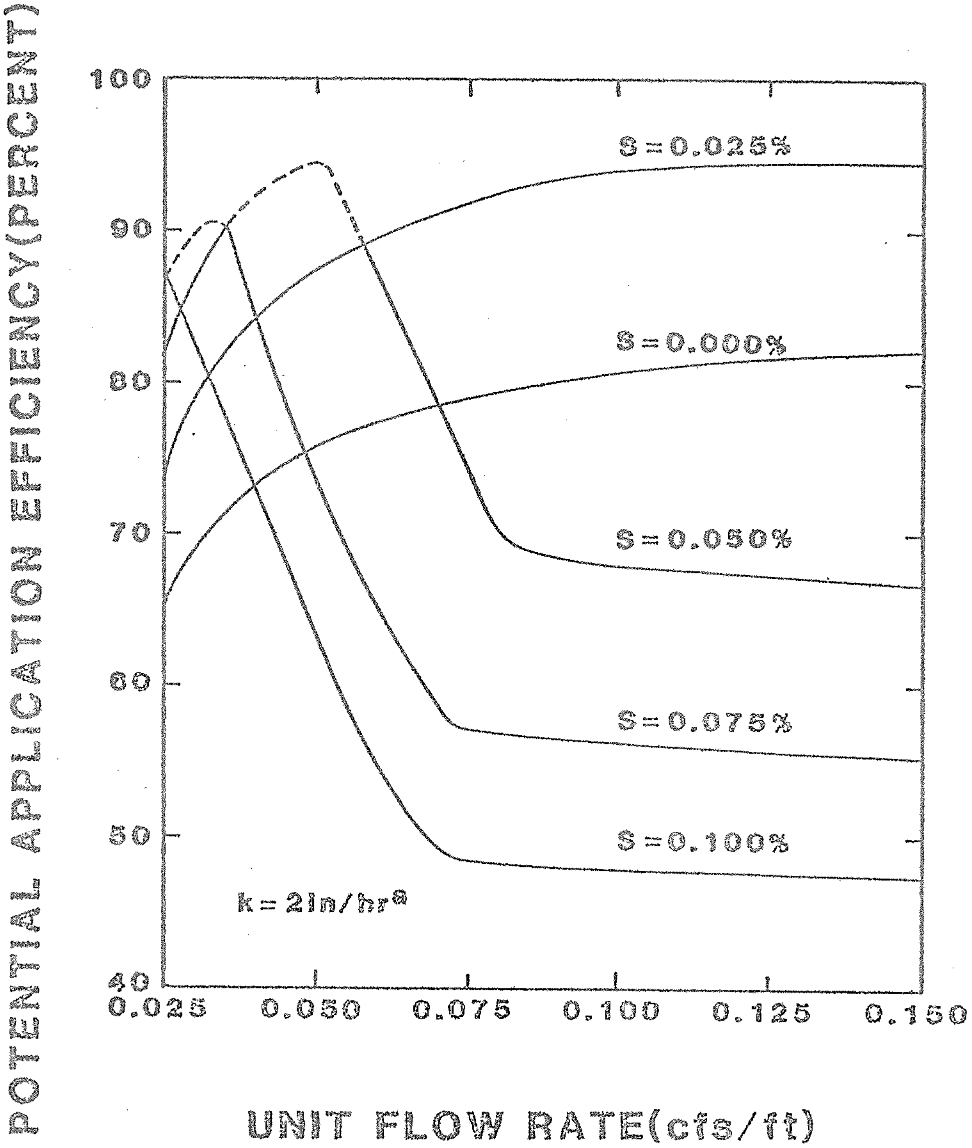

Fig. 2. Potential efficiencies for wet conditions.

TITLE: IRRIGATION WATER, CULTURAL PRACTICES, AND ENERGY ASPECTS OF CANTALOUPE PRODUCTION IN ARID REGIONS

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

In the recent past, and certainly into the near future, increased pressure will come from the consumer for better quality and more nutritious vegetables at a reasonable cost. Arid regions of the southwestern United States have a unique and often envied position of being able to produce vegetables out of season when prices are generally high. However, growers face problems of increased labor and production costs. More important is the urgency to conserve energy and natural resources essential in producing them, e.g., water. The consumptive use of water for cantaloupes in the desert areas of central Arizona has been measured at about 46 cm (18 inches) while in many cases water applied or delivered to a single crop has been double this amount.

Although considerable research has been done with sprinklers, little effort has been made to use efficient level-basin systems, coupled with flat or nearly-flat plantings, application of small amounts of water, and continuous vegetable production. Sprinkler irrigation systems are being use to reduce water requirements for germination, but high rental or purchasing costs and energy costs are making this approach less appealing. Level-basin irrigation is one of the few existing alternatives for improving irrigation efficiency on a large scale without incurring excessive energy costs. Flat plantings have the additional advantages of possibly increasing yields with higher plant populations, reducing cultivation practices, improving salinity management, adapting to mechanical harvest machinery, and shortening the time period between the harvest and planting of another vegetable crop.

A preliminary trial of planting cantaloupes on small, slightly-raised ridges or corrugations was begun in April of 1978. The results were encouraging so it was decided to develop a full-scale field experiment where different irrigation treatments and planting densities with the corrugated planting could be compared to the conventional planting methods. Field procedures, results, and conclusions for this work in 1979 and 1980 with spring cantaloupes are presented in this annual report.

The objectives of this new experiment are: (1) to develop energy-conserving, level-basin irrigation systems that more nearly meet the determined consumptive-use requirements without hindering effective cantaloupe production in terms of yield and quality; (2) to determine if flat plantings, along with increased plant populations, shortened harvest periods, and increased number of cantaloupe crops per year, can be used to increase overall cantaloupe production; and (3) to determine the interrelationships that these changes will create relative to procedures for planting, fertilization, weed control, harvesting, and intensified vegetable production.

Spring Cantaloupe - 1979

FIELD PROCEDURES:

The 1979 cropping season consisted of four planting/plant population treatments: (1) conventional bed at the standard population, 25 cm (10 inches) within row and 150 cm (60 inches) between rows; (2) flat planting at the standard population, same plant dimensions; (3) corrugated planting at a medium population, 25 cm within row and 75 cm (30 inches) between rows; (4) corrugated planting at a high population, 25 cm within row and 50 cm (20 inches) between rows. Irrigation treatments were based on soil-water depletion in the top 60 cm of soil; (1) irrigated when 65% of the soil moisture was used, and (2) irrigated when 75% of the moisture was used. The eight treatment combinations were replicated five times in a randomized-block design for a total of 40 plots. Each individual plot was 6.7 m wide x 18.3 m long (22 x 60 feet). The size of corrugations were approximately 6 cm (2.4 inches) high and 20 cm (7.9 inches) wide.

Top Mark cantaloupe seed was planted and irrigated up for all plots on April 6. The corrugated plantings received 5.6 cm (2.2 inches) on April 6 and 4.1 cm (1.6 inches) on April 12, where the standard beds received 7.6 cm (3.0 inches) on April 6. Plots were thinned on May 10, and 4.9 cm (1.9 inches) of water was applied to the flat planting and 6.5 cm (2.5 inches) of water was applied to the standard beds. On May 30, 6.5 cm (2.5 inches) of water was given to all plots. Thereafter, water application to the medium irrigation treatment included 7.6 cm (3.0 inches) on June 8, June 18, June 27, and July 9, and to the dry treatment consisted of the same amount on June 11, June 22, July 3, and July 12. A total of 51.3 (20.2 inches) of irrigation water and 0.21 cm (0.53 inches) of precipitation was received on all treatments and all plant populations during the growing season. All water applications were measured with a 10 cm (4 inch) propeller-type water meter.

Fertilizer applications consisted of 168 kg/ha (150 lb/acre) of ammonium phosphate (16-20-0) broadcast over the field before planting, 122 kg/ha (109 lb/acre) of urea (46-0-0) after thinning, and 122 kg/ha (109 lb/acre) of urea after early runner. The last two fertilizer applications for all plots were applied along with the irrigation water. The total fertilizer applied was 139 kg/ha (124 lb/acre) of N and 34 kg/ha (30 lb/acre) of P.

Consumptive use was estimated from changes in soil water content at two sites with two locations per site for the medium and dry irrigation treatment with the standard plant population on the corrugated plantings. Soil moisture samples were taken to a depth of 120 cm (4 feet).

Cantaloupe harvest commenced on July 2 for the standard beds and on corrugated plantings on July 9. Harvest lasted until July 25, and melons were sized, counted, and graded three times per week. Four sizes were determined as jumbo 23, 27, 36, or 45, by use of a prescribed sizing template. These sizing numbers are the number of melons that can be packed in a commercial crate (56 x 33 x 33 cm). All melons smaller than 45, rotten, soft, ground spotted, slick, or split were considered culls.

RESULTS AND DISCUSSION:

The 1979 measured seasonal consumptive use was similar for both medium and dry irrigation treatments and averaged 55.1 cm (21.7 inches), as shown in Figure 1. This is not unreasonable since both treatments received the same amount of irrigation water but at different dates. Water applications were at least 6 to 7 days later for the dry compared with the wet irrigation treatment during the period of peak consumptive use rate. The seasonal consumptive use was nearly identical to the total water applied of 51.5 cm (20.7 inches for irrigation water plus precipitation) with a small portion of the consumptive use coming from the soil moisture stored in the root zone prior to planting.

Yields for spring cantaloupes are summarized in Table 1. The effect of timing or scheduling of irrigations is shown by a 25% increase in marketable crates per hectare for the wet over dry treatment. This increase was also significant in terms of total fruit and numbers of larger fruit harvested. The lower production for the dry compared to medium irrigation treatment can be attributed to primarily the application of water too late for the setting and maturing of melons.

Little difference in yield resulted between the standard beds and corrugated plantings at the conventional plant population for both medium and dry treatment. However, on the medium irrigation, doubling of plant populations increased yields by an average of 27% over standard populations. A yield of approximately 1370 crates per hectare (555 crates per acre) on the medium irrigation, corrugated planting, and medium plant population treatment is exceptionally good, since commercial yields for a spring crop in Arizona range from 370 to 620 crates per hectare (150 to 250 crates per acre). With this treatment, the total number of fruit harvested increased by 49% and the number of larger fruit increased by 23% compared with medium irrigation, standard population treatments. Tripling of melon populations produced nearly the number of total harvested fruit, but marketable yields were down because the melons lacked size and the number of culls increased.

Spring Cantaloupe - 1980

FIELD PROCEDURES:

The 1980 cantaloupe experiment was moved from field "A" to field "B" at the Mesa Experiment Farm, University of Arizona, using the same plot layout except the plot width was 10 m (33 feet) instead of 6.7 m (22 feet). This enabled the planting of 25% more area within each individual irrigation plot, while the treatment combinations remained in a randomized-block design with five replicates. Cultivar, water measurement, thinning, soil moisture sampling, and harvesting procedures were identical to those used in 1979. Planting, thinning, first harvest, and final harvest dates were April 11, May 20, July 7, and July 25, respectively.

An initial irrigation for the germination of seeds was given on April 14 with the corrugated plantings and standard beds receiving 5.3 cm (2.1

inches) and 8.4 cm (3.3 inches) of water, respectively. A second irrigation was given on 24 April with the corrugations and standard beds receiving 4.3 cm (1.7 inches) and 6.4 cm (2.5 inches) of water. The purpose of this irrigation was to reduce soil cracking near the young seedlings and soil crusting in order that some deeper seeds might germinate. On May 22, all plots were given an irrigation of 7.9 cm (3.1 inches) of water after thinning was finished. The irrigation treatments subsequently initiated with the medium regime receiving 9.2 cm (3.6 inches) on June 6, 9.4 cm (3.7 inches) on June 18, 9.9 cm (3.9 inches) on June 30, and 5.1 cm (2.0 inches) on July 7. The total irrigation water applied was 51.0 cm (20.1 inches) on the corrugated plantings and 56.2 cm (22.1 inches) on the standard beds for the medium irrigation treatment. The dry irrigation treatment was given 9.9 cm (3.9 inches) on June 10, 11.9 cm (4.7 inches) on June 26, and 5.1 cm (2.0 inches) on July 7, making a total irrigation water application of 44.4 cm (17.5 inches) on the corrugated plantings and 49.6 cm (19.5 inches) on the standard beds for the dry regime. Precipitation amounted to 0.56 cm (0.22 inches) during the entire cropping season.

Fertilizer application amounts were the same in 1980 as 1979 with ammonium phosphate broadcasted before planting, urea applied through irrigation water after thinning, and urea applied through the irrigation water after early runners. The only difference was that the second application of urea was added to the medium irrigation treatment on June 6 and to the dry treatment on June 10. Powdery mildew disease was observed on some plots just before harvesting of the 1980 spring cantaloupes which did not occur on the 1979 spring cantaloupe. Two application of Benomyl fungicide [methyl 1-(butylcarbamoyl) -2 benzimidazolecarbamate] were sprayed when the mildew first appeared. The fungicide did not eliminate the disease; however, the disease problem was not severe such that the melons appeared to mature to full size on the cantaloupe vines.

RESULTS AND DISCUSSION:

The 1980 measured seasonal consumptive use was 43.1 cm (17.0 inches) on the medium irrigation treatment and 39.7 cm (15.6 inches) on the dry irrigation treatment. These values were lower in 1980 than 1979 because temperatures were cooler during the spring of 1980. More water was applied (irrigation water plus precipitation) than the measured consumptive use, about 8.5 cm (3.3 inches) of water on the medium treatment and 10.5 (4.1 inches) on the dry treatment. This additional water requirement was delivered during germination and plant establishment, particularly with the standard beds. Irrigation water applications could have been reduced further by careful management and limiting applications given for the reduction soil crusting and cracking. Soil moisture samples indicated that the dry irrigation treatment was definitely drier than the medium treatment when blossoming and fruit set commenced.

The stand counts after thinning for the higher populations did not quite make the required numbers to be 2 and 3 times the standard population. The medium population averaged 48,500 plants per hectare rather than 51,600;

and the high population averaged 65,550 plants per hectare instead of 77,400. The standard population was very close to the prescribed 25,800 plants per hectare. A summary of 1980 spring cantaloupe production based on the adjusted plant populations is presented in Table 2. With the medium irrigation treatment, there was a 12% increase in marketable crates per hectare when populations were increased by a little more than 75%, whereas yield increased by 27% in 1979 when populations were doubled. Production decreased slightly with the highest plant population, particularly for the dry irrigation treatment; however, the yield reduction with the highest population was not as great in 1980 as in 1979.

The medium irrigation treatment had 35% more marketable yield, 38% more fruit of a size 36 and larger, 15% more total fruit, and 30% less culls than the dry treatment. Many of the culls in the dry treatment were good melons but too small to be considered marketable. It appears that cantaloupes will not withstand water stress during fruit set and early fruit development. Yields on the medium irrigation treatment averaged over 1200 crates per hectare (485 crates per acre).

SUMMARY AND CONCLUSIONS:

Spring cantaloupes were produced under medium and dry irrigation treatments using conventional beds with standard plant populations and a new, nearly-flat corrugation treatment with standard, double, and triple populations. Yield increases of over 25% resulted from doubling of plant populations in the spring of 1979, while marketable yields increased by 12% in 1980 when populations were not quite doubled. The highest melon populations tended to decrease yields and quality for both crops, and the dry irrigation treatment reduced yields by a significant 35% compared with the medium treatment in 1980. Seasonal consumptive use was measured at about 55 cm and 43 cm of water for spring cantaloupes in 1979 and 1980, respectively. The development of high-population, corrugated plantings, coupled with efficient level-basin irrigation systems, has the potential for decreasing water and energy requirements.

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Table 1. Summary of spring cantaloupe yields (mean of 5 replications), 1979.

Irrigation Treatment	Planting Method	Plant Population	Marketable Crates per Hectare	No. Fruit per Plot 36 & Larger	Total No. Fruit per Plot Harvested	Percent Culls
Medium	Bed	25,800/ha	1032.9	58	80	15
Medium	Corrugation	25,800/ha	1122.5	62	90	12
Medium	Corrugation	51,600/ha	1373.2	74	127	26
Medium	Corrugation	77,400/ha	968.9	44	124	37
Dry	Bed	25,800/ha	905.6	50	69	10
Dry	Corrugation	25,800/ha	990.5	55	73	7
Dry	Corrugation	51.600/ha	804.5	36	81	36
Dry	Corrugation	77,400/ha	893.7	45	76	39
			*	*	*	*

* Significant difference at 5% level.

Table 2. Summary of spring cantaloupe yields (mean of 5 replications), 1980.

Irrigation Treatment	Planting Method	Plant Population	Marketable crates per Hectare	No. Fruit per plot 36 & Larger	Total No. Fruit per plot Harvested	Percent Culls
Medium	Bed	25,800/ha	1150.0	63	81	8
Medium	Corrugation	25,800/ha	1149.5	61	84	8
Medium	Corrugation	45,400/ha*	1281.9	55	87	18
Medium	Corrugation	67,100/ha*	1287.1	62	126	25
Dry	Bed	25,800/ha	952.9	53	68	9
Dry	Corrugation	25,800/ha	954.4	51	76	13
Dry	Corrugation	51,600/ha	920.6	46	100	28
Dry	Corrugation	64,000/ha*	787.7	25	86	34
			**	***	***	***

* Numbers adjusted because of less than adequate stands.

** Significant difference at 5% level.

*** Significant difference at 1% level.

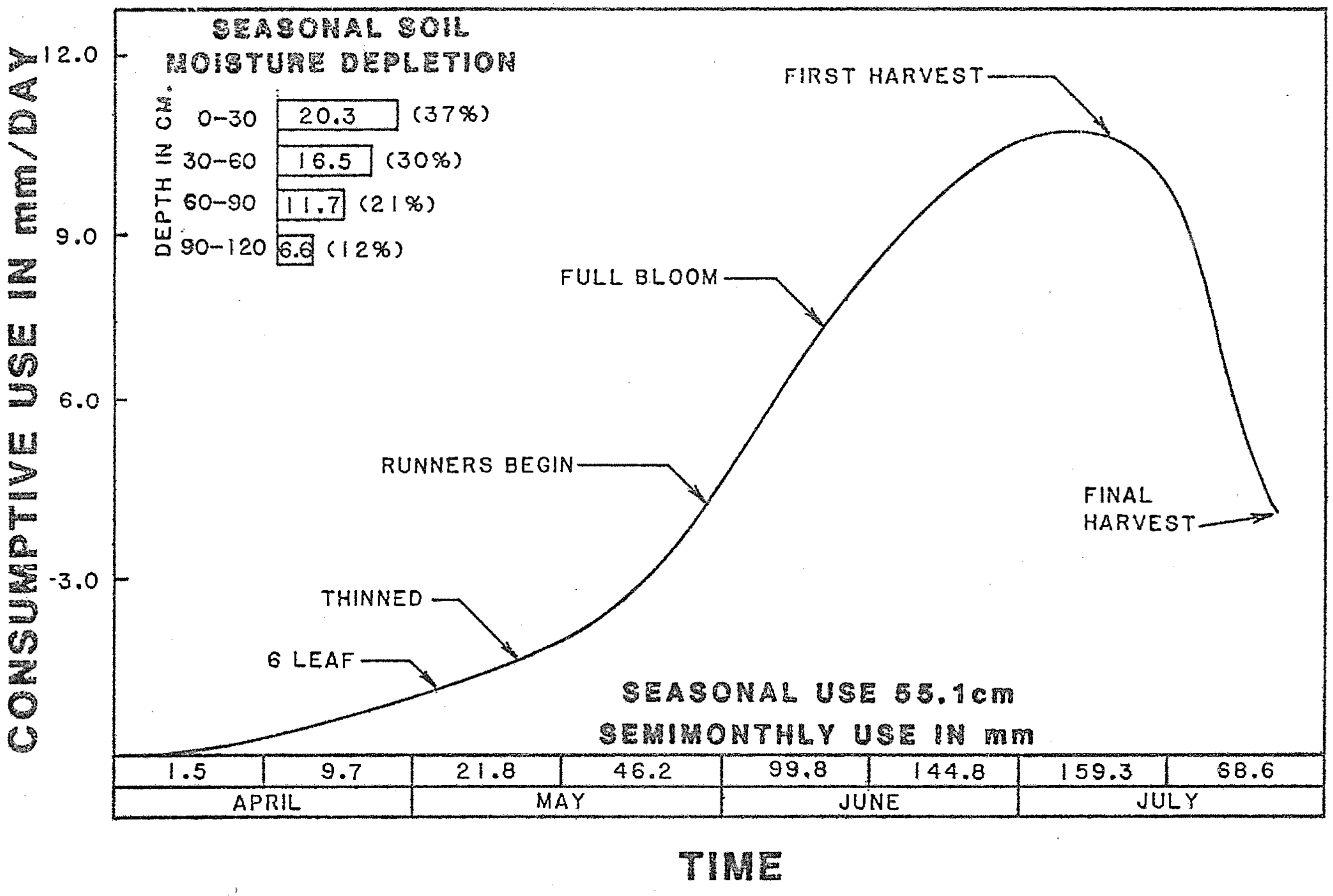

Figure 1. Mean consumptive use curve for medium and dry irrigation treatments on spring cantaloupes at Mesa, Arizona, 1979.

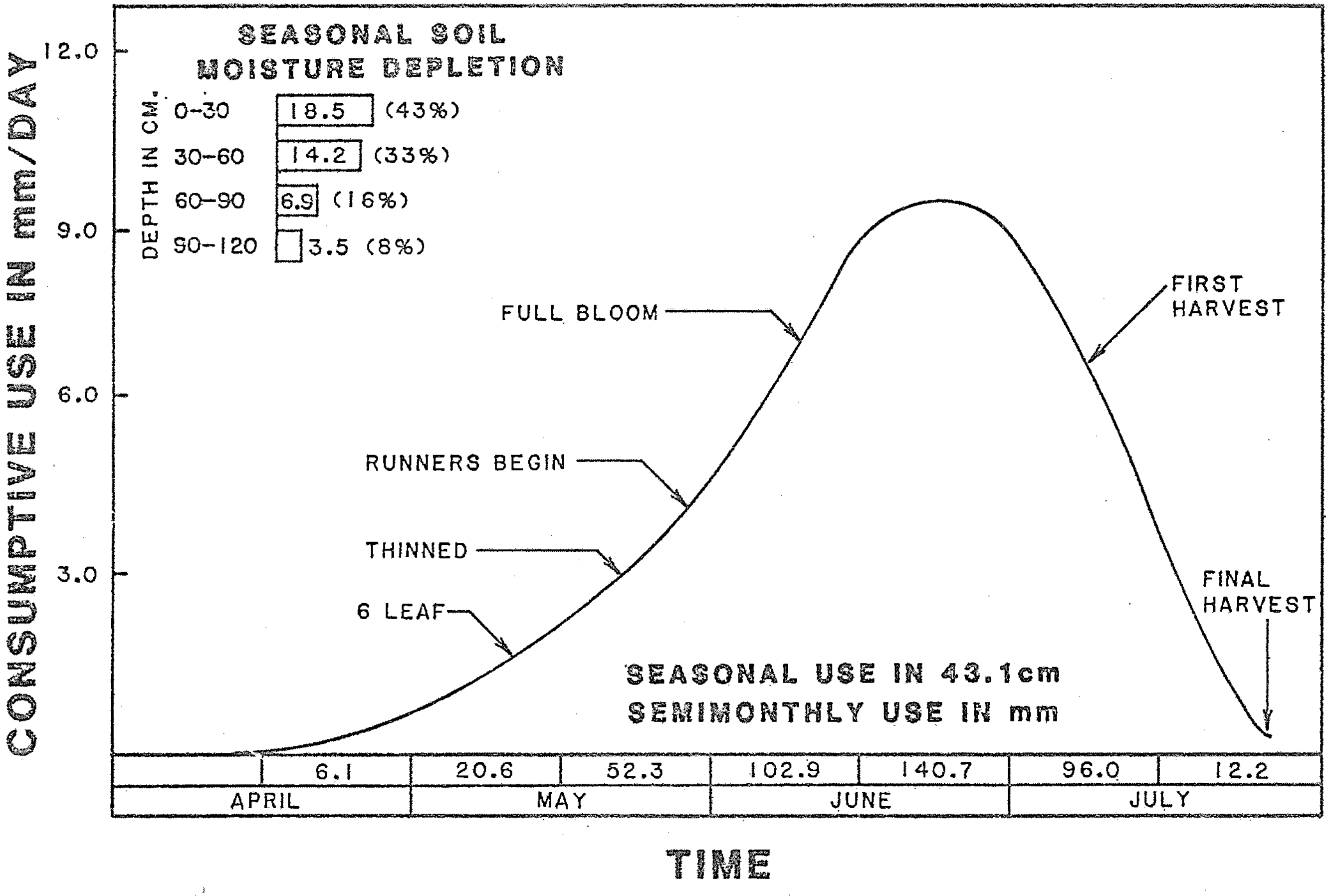

Figure 2. Mean consumptive use curve for a medium irrigation treatment on spring cantaloupes at Mesa, Arizona, 1980.

TITLE: IRRIGATION WATER MANAGEMENT FOR RICE PRODUCTION IN THE SOUTHWESTERN UNITED STATES

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

Rice research was started in 1979 at two locations in Arizona (Yuma and Safford) and one in California. The objectives of these new experiments are: (1) to determine rice varieties suitable for an intermittent irrigation schedule; (2) to evaluate the effects of irrigation regime and planting data on non-paddy rice production; (3) to determine water requirements and estimate consumptive use for southwestern desert climates, utilizing level-basin irrigation systems.

Numerous books and manuscripts have been written on rice production. Some of the more recent are: Rice Production Manual, IRRI, Philippines (1970); Climate and Rice, IRRI, Philippines (1976); Rice in the United States: Varieties and Production, USDA-ARS, Handbook No. 289 (1973); Weed Control in the United States, Rice Production, USDA-ARS, Handbook No. 497 (1977); Six Decades of Rice Research in Texas, Research Monograph 4 (1975); Rice: Production and Utilization (1980); and many other articles from the Texas, Gulf Coast, and California rice growing areas. Generally these publications deal with paddy rice, luxuriant water supplies, and not in areas of low humidity, high temperatures, or desert areas such as Arizona or southern California. Rice provides a third of the world's population with more than half of their calories and nearly half of their protein.

J. C. O'Toole and T. T. Chang, IRRI, Philippines, in a chapter titled, "Drought Resistance in Cereals - Rice: A Case Study," in the book, Stress Physiology in Plants (1980) attempted to stimulate a greater appreciation for drought resistance in rice and to encourage more fundamental research of the soil-plant-water relationships. Their conclusions were: (1) the effectiveness of any attempt to improve drought resistance of rice must be based on a thorough knowledge of, and appreciation for, the locational and temporal specificity that characterizes a particular drought condition; and (2) the complexity of ecological conditions to which rice has adapted, especially the breadth of hydrological conditions indicates that great variability of water-related adaptations exist within the germplasm. They also pointed out that drought resistance in terms of drought avoidance and drought tolerance should be considered together and not as separate or unrelated effects.

Farmers are always looking for new or alternate crops with an economical potential, and the farmers in the southwestern United States are no exception. With the advent of level-basin irrigation systems, small applications of water (3 to 5 cm) can be applied at high water application and distribution efficiency. Intermittent irrigation scheduling, coupled with level-basin practices, could allow a continuous near-saturated soil and would conserve both water and energy in terms of less pumping and labor.

Many locations in the southwestern United States have certain characteristics conducive to rice production such as long, warm growing seasons; low-intake, silty-clay soils; level-basin irrigation systems, excellent farm managers, and a need for new, highly-mechanized, low-labor crops. Areas having these characteristics where research can be conducted are El Centro, California; Yuma, Arizona; Safford, Arizona; and many other locations in Arizona, California, New Mexico, and western Texas. Although 60 percent of the annual American rice crop of seven million short tons is exported and the additional need for rice in the United States at this time may be small, the future need for expanded rice production under desert or semi-arid conditions in this country and throughout the world, where water is limited, is a definite possibility.

El Centro, California

FIELD PROCEDURES:

The primary purpose of the 1979 and 1980 investigations at the Imperial Valley Field Station, El Centro, California, were to identify rice varieties suitable for desert irrigation practices. In the 1979 irrigation experiment, 50 varieties were planted on 11 May, 11 June, and 11 July, using four irrigation schedules of paddy, 3-, 6-, and 9-days between water applications. Each variety was planted in rows 2.4 m (8 feet) long on 30 cm (12 inch) centers and replicated four times. A seeding rate of 8 grams per row was used. Ordram (molinate, S-Ethyl hexahydro-1 H-azepine-1-carbothioate) was applied at about 34 kg/hectare (30 pounds/acre) as a preplant herbicide. Nitrogen fertilizer was applied at 112 kg/hectare (100 pounds/acre), consisting of 32 kg preplant, 32 kg at tillering, 16 kg at early boot, and 32 kg at late boot. In addition to the 50-variety study, an introduction nursery with about 1,300 varieties, an observation nursery with about 161 entries, and a "blanking" experiment with 32 entries were grown to assist in selecting new varieities for the 1980 irrigation study.

In the 1980 irrigation experiment, a new set of 50 varieties was planted on 19 April, 16 May, and 19 June under paddy, 3- and 6-day irrigation regimes with four replications. Also, it was decided to see if some of the best lines could be improved through natural selection. To test this hypothesis, seed was planted from about five varieties originating from the paddy, 3- and 6-day irrigation treatments used in 1979. The lines handled in this manner were IR 22, IV 213, IV 330-1, IV 40, TI, and IR 1108-3-5-3-2.

The hypothesis of natural selection for seed set under conditions of intermittent flooding was further tested in a 50-variety natural selection experiment. Seed planted in this experiment was from varieties that produced seed in the 9-day irrigation treatments as well as from other varieties capable of producing an appreciable amount of seed with minimum water applications. An introduction nursery with about 1200 varieties and an observational nursery with about 70 varieties having limited quantities of seed available, were also planted in 1980.

RESULTS AND DISCUSSION:

Tables 1, 2, and 3 include information on seven characteristics for 50 varieties, four irrigation treatments, and three planting dates in 1979. Variability existed among the characteristics, but certain generalizations can be made. If all varieties and treatments are considered, the earliest or 11 May planting date performed best. The main reason was that the reduced number of water applications (from flood to an irrigation every 9 days) delayed the date of heading as much as 30 days for most lines. This long delay in heading tended to extend the growing period into the fall where heading and/or maturity were impossible, thus reducing yield. Date of maturity was not obtained, but it appeared that the reduced number of water applications also extended the time between heading and maturity.

Decreasing the number of irrigations affected other characteristics besides days to heading. For many varieties, panicle exsertion was not affected. However, when affected, exsertion was reduced as the interval between irrigation increased (number of irrigations decreased). When differences in grain type were found, the change was toward a shorter or smaller grain as less water was applied. No information was obtained on grain weight, but there appeared from visual observations to be a decrease as water application decreased. As might be expected, seed blanking (no seeds in the glumes) increased drastically as less water was applied. For many lines blanking was 90 to 100% in the 6-day and 9-day irrigation treatments. For some varieties, such as those from the southcentral United States, blanking was 90% or greater with the 3-day irrigation treatment. However, important differences were found in a variety's ability to set seed with a lower number of water applications. Plant height and yield decreased as water applications were reduced, and yield was closely related to percent blanking.

Eighteen lines were selected from the 1979 irrigation experiment for planting in 1980 irrigation study, primarily because they appeared to have reduced blanking and/or good production over a range of treatments. Some of the more promising varieties were IR 22, IR 26, IV 213, and IV 404. Figure 1 shows the effect of irrigation treatments and planting dates for IR 22 and IV 213. Individual differences can be observed between varieties but the general trends are similar to those described previously.

Results from the 1980 investigations are still being analyzed. Data was obtained on the same characteristics as in 1979 plus three additional characteristics - general appearance, save or discard, and stem angle. In general, the varietal reaction to planting dates and irrigation treatments were similar. For example, decreased number of water applications resulted in later heading dates, poorer panicle exsertion, smaller grain size, less lodging, shorter stature, and lower yields. The effects from natural selection for reduced water applications is still being analyzed. Of the 50 entries in the 1980 irrigation experiment, 31 were selected for planting in the 1981 irrigation experiment. Three lines from the natural selection trial and 11 lines from the introduction nursery will also be planted in the 1981 irrigation experiment.

In 1980, data was obtained on soil salinity before and after giving an irrigation. In general, leaching was improved with the intermittent irrigation treatments (3- and 6-day intervals between irrigations) over the paddy treatment. More leaching occurred at the 30 cm (1 foot) soil depth than at the 60 cm (2 foot) depth. Little difference in the leaching of salts was observed for the different planting dates.

Yuma, Arizona

FIELD PROCEDURES:

Four different rice varieties were planted on three dates (8 May, 30 May, and 20 June) in the 1979 irrigation experiment. The four varieties were Calrose 76, Nato, Labelle, and Lebonnet. For each of the planting dates, three irrigation treatments included applying irrigation water either twice a week, once a week, or every 10 days. Each variety was replicated four times within each irrigation treatment. The drilling rate was 123 kg/hectare (110 lbs/acre), and the rows were spaced 18 cm (7 inches) apart. In addition, an observation nursery of 30 rice varieties was planted on all three planting dates. In 1980, six varieties (Calrose 76, LaBelle, IV 213, IR 22, IR 1108-3-5-3-2, and M 101) were planted on six different dates (29 February, 30 March, 16 April, 15 May, 16 June, and 8 July). The same irrigation treatments were used in 1980 as 1979, and an observation nursery with 37 rice varieties was planted again on the six dates.

A preplant application of Ordram herbicide (molinate, S-Ethyl hexahydro-1 H-azepine-1-carbothioate) at a rate of 22 to 34 kg/hectare (20 to 30 lbs/acre) was applied for general weed control in both years. In 1980, Stam M4 (propanil, 3', 4' - Dichlorophenylpropionanilide) was sprayed for post-emergent control of barnyard grass. Several applications of Sevin (carbaryl, 1-Naphthyl N-methylcarbamate) and Diazinon insecticide [0,0-Diethyl 0-(2-isopropyl-4-methyl-6-pyrimidinyl) phosphorothiate] were applied during the summer months, mainly for thrips and flea beetles. Nitrogen fertilizer in the form of urea was broadcasted prior to planting at 56 kg/hectare (50 lbs/acre) of N, followed by another 56 kg/hectare after tillering and before initial heading.

Irrigation water applications were measured with a 10 cm (4 inch) propeller-type water meter, and detailed rice phenology was recorded on all plots. Chemical leaf analysis for nitrogen, phosphorous, potassium, and minor elements were made on the rice leaves at three times during the growing season. The rice was harvested when an entire planting date reached maturity, and yields were based on a 1.37 m^2 (14.7 sq. feet) sampling area. Seed weight and nutrient analysis was also determined from the harvested grain.

RESULTS AND DISCUSSION:

Germination took place in less than 8 days for all planting dates and varieties in 1979, and the time period from planting to heading (approximately 98 days) was nearly the same for the first two planting dates (9 May and 30 May) and slightly faster (83 days) for the late planting (20 June), as shown in Table 5. The total water applied (irrigation water plus precipitation) with two irrigations per week was nearly the same as the seasonal pan evaporation. With a single irrigation every week or 10 days, the water applied was less than pan evaporation for all planting dates (Table 6). On the 10-day irrigation frequency, irrigations were increased to twice weekly in October because of the visual plant-water stress; however, the added water late in the growing season did not appear to improve production.

Table 7 shows the stepwise increase in rice yields with increased irrigation frequencies. The highest yielder in the 1979 irrigation experiment was the Calrose 76 variety, which averaged about 1650 kg/hectare (1500 lbs/acre) for all planting dates. The next highest yielding variety was Labelle, although this variety yielded less than half that obtained by Calrose 76. The rice yields from the plots irrigated on a 10-day interval were usually below 112 kg/hectare (100 lbs/acre). Indications were that an earlier planting date would be beneficial for some varieties.

Chemical leaf analysis of nitrogen, phosphorous, and iron for all rice varieties is shown in Table 8. Nitrogen levels in the mature leaves were in the adequate range for all sampling periods. While phosphorous levels were adequate initially, they may have fell slightly below the adequacy level 80 days after planting. This is based on plant tissue guide for California rice production (Table 9), where rice is grown under continuous flooding (paddy). Generally, a flooded soil will provide a higher nutrient availability and minimum loss of nutrients from fertilizer and soil. Under flooded conditions, some fertilizer may be combined with organic forms of soil microorganisms in the soil and be released too late for crop uptake. Under upland (rainfed) conditions, nitrogen is lost directly by ammonia volatilization. DeDatta, IRRI, Philippines, (1974) indicates that 52% of the nitrogen applied in taken up by the rice plant under flooded soils compared to 28% under upland soils without incorporation of the rice straw. When the rice straw was incorporated, plant uptake was only 3% for flooded and 16% for upland rice. Mikkelsen and DeDatta (1980) point out that most upland rice varieties do not respond well to nitrogen, and nitrogen fertilization increases susceptibility to blasting and lodging. However, they point out that the development of new varieties with higher levels of blast resistance could reduce this problem. We could also speculate that nitrogen efficiency could be greater with direct-seeded, intermittent irrigated rice than for upland rice, where amounts and distribution can be erratic. After more drought tolerant varieties are found for the southwestern United States, a closer look at the fertilizer application rate and utilization may be required.

The 1978 nutrient levels from the harvested grain are presented in Table 9. There appears to be little difference between the harvested varieties, irrigation treatments, or planting dates for most of the nutrient levels. The zinc levels in the grain could be slightly low. Masironi et al. (1977) sampled 27 unpolished and 100 polished varieties, not corrected for moisture, and found mean values of 16.4 and 13.7 μg/g (ppm) Zn, respectively.

On the earliest planting date in 1980 (29 February) the number of days from planting to germination was about five times longer than compared with the later planting dates (16 June and 8 July). Table 9 suggests that average daytime temperatures should reach nearly 30°C (85°F) and night temperatures should be above 10°C (50°F). Undoubtedly, soil temperature is critical for the germination of rice in a relatively short period of time (less than 14 days), although soil temperatures were not measured. The February planting was probably too early, whereas the late March or early April planting appeared to provide a more reasonable timetable for germination. The variety difference in germination time was not as great as the difference due to date of planting. Heading and panicle exsertion were considerably earlier for the M 101 variety than the Calrose 76, Labelle, IV 213, IR 22 and IR 1108-3-5-3-2 varieties. For the later five varieties, heading began at approximately the same date (1 August) for the first three planting dates. This indicates that planting as early as February or March may not mean an earlier harvest date (Table 10). With a later March or April planting, a 110- to 120-day period from planting to heading could be estimated for the IV 213, IR 22, and IR 1108-3-5-3-2 varieties.

From germination until approximately 15 to 20 cm (6 to 8 inches) in plant height, all the 1980 varieties appeared to grow at about the same rate. After that period of time (data not shown), the Calrose 76 and Labelle varieties grew taller than the other four varieties. Average plant heights, before harvest on the first three planting dates with two irrigations per week, were: Calrose 76 - 76 cm (30 inches); Labelle - 76 cm (30 inches); IV 213 - 60 cm (27 inches); IR 22 - 60 cm (27 inches); IR 1108-3-5-3-2 - 60 cm (27 inches); and M 101 - 66 cm (26 inches). Plant heights tended to decrease with fewer number of irrigations and with a planting date in May or later for these varieties.

Table 11 summarizes the seasonal water applied and pan evaporation for 1980. Again, two irrigations per week resulted in a total water applied (irrigation water plus precipitation) nearly equal to the pan evaporation. The wettest irrigation treatment represented a total water applied equivalent to about 254 cm (100 inches) of water for the first four planting dates (29 February, 19 March, 16 April, and 14 May). While on the last two planting dates (16 June and 8 July), the total water applied was somewhat less than 200 cm (80 inches) for the most frequent irrigation schedule. With an irrigation once a week, the total water applied was reduced to about 175 cm (70 inches), and the 10-day irrigation treatment was about 25 cm (10 inches) less than this intermediate irrigation regime. Although a smaller amount of irrigation water was applied on the June and July plantings, the six varieties neither fully pollinated during an extremely hot September (maximum air temperature averaged over 37°C) nor completely matured during October and November. In fact, 1980 temperatures in excess of (100°F) started in the middle part of June and continued through the first part of October. With a later April or May planting, a potential still exists for applying less than 150 cm (60 inches) of irrigation water, where soil intake rates are lower than the plots in this study and water applications of less than 5 cm (2 inches) are given with each irrigation.

Seasonal evapotranspiration for rice under an intermittent irrigation schedule should be considerably less than the irrigation water applied or irrigation water requirement for these initial studies. After the most promising rice variety and planting date has been determined, a seasonal evapotranspiration curve will be measured and used to improve the scheduling of intermittent irrigations for rice.

Yields and grain weights for selected 1980 rice varieties are presented in Table 12 for various planting dates, varieties, and irrigation treatments. Yields are reported only where significant production was recorded from nearly all replicates. Little grain was harvested from the June and July plantings, and only a few varieties were harvested from the twice a week irrigation treatment for the May planting. The three highest yielding varieties were IR 22, IV 213, and IV 1108-3-5-3-2. For each of these varieties, the greatest yield was obtained from the twice weekly irrigation treatment and the 19 March planting date. Yields generally declined when irrigations were decreased to once weekly or every 10 days. However, IR 22 and IR 1108-3-5-3-2 achieved the same or slightly larger yields for the weekly compared with the twice weekly irrigation regime for the 19 February and 19 March planting dates. Therefore, it appears that the interval between irrigations could possibly be extended beyond every 3 or 4 days depending on the crop growth stage. Also, the three most promising varieties have a potential yield of about 5000 to 7000 kg/hectare (4500 to 6500 lbs/acre) under an arid climate similar to Yuma, Arizona. Little difference in the grain weight was evident between the treatments where rice was produced. Additional quality measurements are still analyzed from the 1980 harvested grain.

Plant analysis of mature leaves for all varieties at three growth stages is shown in Table 13. No distinct deficiencies in nitrogen, phosphate-phosphorous, potassium, or zinc were observed in 1980, based on plant tissue levels suggested for California rice production (Table 9). Typically, the nitrogen, phosphorous, and potassium values decreased with sampling dates. On the third planting date (16 April), there appears to be some increase in nitrogen, phosphorous, and potassium at the 65-day sampling. Generally, the nutrient levels were somewhat higher in 1980 than in 1979, and nitrogen percentages in the leaves were slightly higher for the later planting dates than the earlier planting dates. Little difference in the nutrient levels of the harvested grain in terms of nitrogen, potassium, phosphorous, iron, manganese, zinc, or copper was observed between varieties, irrigation treatments, or planting dates. Zinc levels in the unpolished grain were considerably higher in 1980 than 1979, which was possibly due to the improved varieties.

From the 1979 observation nursery of 30 rice varieties, some of the more promising varieties were Calrose 76, IR 22, IR 28, IR 30, and T-1. Eighteen were selected for replanting in the 1980 observation nursery of 37 varieties. The more promising varieties included Calrose 76, IR 22, IR 28, IV 213, IV 330-1, IV 404, IR 1108-3-5-3-2, T-1, and Taichung 181. Sixteen varieties were selected from 1980 for planting in the 1981 observation nursery of 32 varieties.

Safford, Arizona

FIELD PROCEDURES:

In the 1979 irrigation study, five rice varieties (Calrose 76, Mars, Newrex, Lebonnet, and Starbonnet) were planted on 15 May and 14 June. The same irrigation treatments of twice weekly, weekly, and every 10 days between irrigations were used in Safford as for Yuma, Arizona. Each variety plot was replicated four times within every irrigation treatment, and its size was 2.1 m (7 feet) wide and 4.6 m (15 feet) long. The planting rate was 123 kg/hectare (110 lbs/acre) of seed, and the rows were spaced 18 cm (7 inches) apart. The same five rice varieties were again planted in the 1980 irrigation experiment, except on 9 May and 5 June. An observation nursery of 30 varieties in 1979 and 37 varieties in 1980, identical to the Yuma nurseries, were also planted two times and irrigated twice weekly.

A preplant application of Ordram herbicide (molinate, S-Ethyl hexahydro-1-H-azepine-1-carbothioate) at a rate of 22 to 34 kg/hectare (20 to 30 lbs/acre) was applied for general weed control in both years. Nitrogen fertilizer in the form of urea was broadcasted before planting at 50 kg/hectare (50 lbs/acre)of N, followed by another 56 kg/hectare after tillering and before initial heading. Irrigation water applications were measured with a 10 cm (4 inch) propeller-type water meter. The first planting date in 1980 was harvested on 29 October, and the second planting date was harvested on 4 December. Yield samples were taken from a 1.37 m^2 (14.7 sq. feet) plot area and seed weight was also determined from the harvested grain.

RESULTS AND DISCUSSION:

The rice seed began to germinate in both years about 7 to 10 days after planting for all varieties and planting dates. The initial seedling emergence was very uniform in 1979; however, when the plants reached a height of 5 cm (2 to 3 inches) the young seedlings began to die. Seedling death was eventually attributed to a high pH and sodium condition in the soil. Typically, the soil on the Safford Experiment Station has a pH above 8.0, an electrical conductivity above 5.0 mmhos/cm, and soluble sodium of about 1000 mg/l near the soil surface. Irrigation water on the farm comes from two sources - Gila river water and a groundwater well. The river water has a pH of about 6.9, an electrical conductivity of 0.6 mmhos/cm, and soluble sodium of 80 mg/l, whereas the well has a pH of about 7.0, an electrical conductivity over 2.0 mmhos/cm, and soluble sodium over 250 mg/l. The water quality from the irrigation well has been steadily improving over the past decade.

After experiencing stand establishment problems with the two planting dates in 1979, different amounts of sulfuric acid (H_2SO_4) were applied to small field plots before rice was planted. Also, the soil from a 0-10 cm (0-4 inches) depth and water from the irrigation well was brought to Phoenix, where various amounts of sulfuric acid were tried in small pots in a greenhouse. From both the small plots and principally the greenhouse pots, it appeared that 4.5 to 6.7 metric tons/hectare (2 to 3 tons/acre) of sulfuric acid would alleviate the soil toxicity. By this time, it was too late in the season to replant the larger plots and conduct an irrigation experiment.

Stand establishment in 1980 was markedly improved by applying sulfuric acid at 6.7 metric tons/acre (3 tons/acre) prior to planting. Table 14 indicates that the acid reduced the pH, electrical conductivity, and sodium concentration in the top 0-5 cm (0-3 inches) of soil to a small extent and its effects persisted throughout the growing season. However, the sulfuric acid appears to provide little benefit at lower depths in the soil profile. Although the use of acid was successful, about 20 percent of the young rice seedlings did die during the third to fourth week after planting. Once again, different amounts of sulfuric acid were applied to small test plots suggesting that the 6.7 metric tons/hectare was adequate but 11.2 to 13.4 metric tons/hectare (5 to 6 tons/acre) could further improve plant growth. Therefore, plans for 1981 include increasing the seeding rate and using 13.4 metric tons/hectare of sulfuric acid.

Yields and grain weight for the Calrose 76 variety are presented in Table 15. The yield approached 3400 kg/hectare (3000 lbs/acre) and the seed weight averaged 10.8 grams/500 grains. The second best variety in the irrigation study was Lebonnet, which did not pollinate for all treatments and replications. The Calrose 76 yielded almost as good for the 10-day irrigations as the twice weekly or weekly irrigation schedule. This can be attributed to high water-holding capacity and a low infiltration rate for the Safford soil. In terms of the 1980 observational nursery, some promising varieties were Nato, Labelle, Taichung 181, and M 7. Additional California varieties besides Calrose 76 and M 7 will be planted in 1981.

SUMMARY AND CONCLUSIONS:

Rice was produced at the Imperial Valley Experiment Station, El Centro, California; the Yuma Valley Experiment Station, Yuma, Arizona; and the Safford Experiment Station, Safford, Arizona, in both 1979 and 1980. At El Centro, California, over 2000 varieties were planted several times in different experiments each year with the primary purpose of selecting and adaptiving rice varieties suitable for desert climates. In the irrigation experiments, 50 varieties were irrigated under paddy, 3-day, and 6-day irrigation regimes. Eighteen lines were selected from the 1979 irrigation study for further planting in 1980, while 31 varieties were selected from the 1980 irrigation study for repeated planting in 1981. In terms of general plant-water stress characteristics, decreasing the number of water applications typically resulted in later heading dates, later maturity dates, poorer panicle exsertion, smaller grain size, less lodging, shorter stature, and lower yields. The more promising varieties originated from the Philippines, where some of these plant-water stress characteristics were not as pronounced.

At Yuma, Arizona, four varieties were planted on three dates in 1979, and six varieties were planted on six dates in 1980 under twice weekly, weekly, and 10-day irrigation treatments. Three lines (IV 22, IV 213, and IR 1108-3-5-3-2) showed the most promise in 1980 for the planting dates of late February through April with a potential yield of as high as 7000 kg/hectare (6500 lbs/acre). Nutrient levels in mature plant leaves and unpolished grain suggested minimal fertility problems with 112 kg/hectare (100 lbs/acre) of nitrogen supplied in two applications under the intermittent irrigation practices.

At Safford, Arizona, with a more moderate heat and humidity stress than El Centro, California, or Yuma, Arizona, five varieties of rice were planted twice using irrigation treatments of twice weekly, weekly, and every 10 days. Stand establishment was improved in 1980 compared with 1979 by applying 6.7 metric tons/hectare (3 tons/acre) of sulfuric acid before planting to alleviate a high sodium and pH soil condition. 1980 yields appeared to be higher for May compared to the June planting date, and the Calrose 76 variety was the most promising.

Rice continues to be the main staple food and major source of protein for a large part of the world. While the physiologic and genetic aspects of crop improvement relative to water stress have been extensively researched for other cereal crops, rice has largely been ignored. The intermittent irrigation of rice and usage of cultivation practices similar to other cereal grains, along with the development and selection of heat-tolerant rice varieties, could expand and improve rice production for semi-arid regions of the world.

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Table 1. Rice irrigation experiment planted on 11 May 1979 (Julian Date 132) at El Centro, California.

Variety	Entry No. and Treatment[1]		Julian Heading Date	Panicle Exsertion[2]	Grain Type[3]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4]
IR 22	1	F	246.0	1.5	2.0	1.5	7.0	70.0	816.0
		3	256.0	1.5	2.5	1.0	19.5	57.0	244.0
		6	264.5	1.0	2.0	1.0	55.0	50.5	106.0
		9	277.5	1.5	1.5	0	94.0	36.5	0
IR 26	2	F	246.0	2.0	1.5	1.5	2.5	68.5	678.5
		3	256.0	1.5	2.0	1.0	23.5	59.0	188.5
		6	267.0	1.5	2.0	0	74.5	46.0	18.5
		9	285.5	2.0	1.5	0	100.0	34.0	0
IR 28	3	F	288.0	1.0	1.5	7.0	10.0	66.0	101.5
		3	234.0	1.0	2.5	1.0	30.0	53.0	45.0
		6	243.5	1.5	2.5	0.5	87.0	52.0	7.5
		9	268.0	2.0	2.0	0	85.0	36.5	1.0
IR 29	4	F	240.0	2.0	2.0	3.5	2.5	63.5	214.0
		3	250.0	1.5	2.5	1.0	15.5	59.0	72.0
		6	256.0	2.0	2.0	0.5	28.0	47.0	62.0
		9	270.5	2.0	1.5	0	96.0	35.0	0
IV 22	5	F	232.0	1.0	2.0	3.0	6.5	63.5	356.0
		3	246.0	1.5	2.0	0	31.5	67.5	119.0
		6	251.5	1.5	1.0	0	56.5	47.5	42.5
		9	265.5	2.0	1.5	0	69.5	39.0	10.0
IV 56	6	F	237.5	2.0	2.0	2.5	22.0	65.5	265.0
		3	246.0	1.5	2.0	1.0	54.5	53.5	117.0
		6	248.0	2.0	2.5	0	94.0	49.5	23.0
		9	265.5	2.0	1.0	0	100.0	38.5	0
IV 66	7	F	240.0	2.0	1.5	1.5	19.0	56.0	267.5
		3	254.0	2.0	1.5	1.0	60.5	44.0	113.0
		6	263.5	2.0	1.5	0.5	89.5	33.0	22.5
		9	274.0	2.0	1.0	0	97.5	31.5	0
IV 213	8	F	232.0	2.0	2.0	1.5	11.0	62.0	271.0
		3	242.5	1.5	2.0	1.0	22.5	57.0	245.0
		6	248.0	1.5	1.5	0.5	48.0	54.5	69.5
		9	264.5	2.0	1.5	0	100.0	41.0	0
IV 237	9	F	239.0	1.0	2.0	1.0	11.0	67.0	374.0
		3	248.0	1.0	2.0	1.0	26.5	56.0	145.0
		6	254.0	1.5	2.0	0	55.0	24.0	76.5
		9	274.0	2.0	1.0	0	90.0	37.0	1.0
IV 330-1	10	F	236.0	2.0	2.0	2.0	3.5	61.0	272.5
		3	248.0	1.5	1.5	1.5	26.5	55.0	213.0
		6	251.5	2.0	2.0	0.5	83.0	48.0	0
		9	258.0	2.0	2.0	0	100.0	39.0	0.5
IV 404	11	F	236.5	1.5	2.0	2.0	12.0	73.5	705.5
		3	246.0	2.0	2.0	1.0	28.0	59.0	266.5
		6	249.5	1.0	2.5	1.0	44.0	51.0	95.5
		9	260.5	2.0	1.0	0	95.5	40.5	1.0
Calrose 76	12	F	223.5	1.0	1.5	0.5	7.5	75.0	314.0
		3	236.5	1.0	2.0	1.0	37.5	64.5	140.0
		6	243.5	1.0	2.0	0	98.0	52.5	5.0
		9	265.5	1.0	1.0	0	100.0	37.5	0
Labelle	13	F	214.0	1.0	2.0	0	71.0	82.0	51.0
		3	228.0	1.0	2.5	0.5	77.0	65.5	38.5
		6	234.0	1.0	3.0	0	93.5	60.0	0
		9	257.5	1.5	1.0	0	100.0	46.0	0

Table 1. (Continued)

Variety	Entry No. and Treatment[1]		Julian Heading Date	Panicle Exsertion[2]	Grain Type[3]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4]
Nato	14	F	232.0	1.0	1.0	0.5	32.5	84.5	330.5
		3	241.0	1.0	2.0	0	73.0	76.5	0
		6	253.0	1.0	1.5	1.0	98.0	56.5	0
		9	267.0	2.0	1.0	0	100.0	48.0	0
Lebonnet	15	F	222.5	1.0	3.0	0	33.5	91.5	136.5
		3	229.0	2.0	3.0	0	99.5	67.5	0
		6	237.5	2.0	3.0	0	100.0	56.5	0
		9	256.0	2.0	3.0	0	90.5	43.0	0
Starbonnet	16	F	240.0	1.0	2.5	0	29.5	90.0	129.0
		3	251.5	1.0	3.0	0	95.0	79.0	1.5
		6	269.0	1.0	2.5	0	100.0	56.0	0
		9	274.0	1.0	2.0	0	85.5	50.0	0
Mars	17	F	225.0	1.0	2.5	1.0	45.0	79.5	322.5
		3	237.5	1.0	2.5	0.5	88.0	73.5	8.5
		6	251.5	1.5	2.0	0	100.0	50.0	0
		9	297.0	2.0	1.0	0	100.0	31.0	0
Newrex	18	F	222.5	1.0	2.5	0	35.5	78.5	95.5
		3	230.5	1.5	3.0	0	93.5	71.5	0
		6	223.5	1.0	2.3	0	98.0	56.0	0
		9	258.5	2.0	2.5	0	92.0	50.0	0
M 101	19	F	208.0	1.0	1.0	0	40.5	56.0	267.5
		3	214.0	1.0	1.5	0	96.0	51.0	40.0
		6	216.5	1.5	2.0	0	99.5	44.0	20.0
		9	238.5	1.5	2.0	0	98.0	45.0	0
Benkei	20	F	241.0	1.0	2.0	2.5	13.0	90.5	209.0
		3	248.0	1.0	1.5	0.5	82.0	84.5	16.5
		6	254.0	1.0	1.0	0	100.0	58.5	0
		9	265.5	1.5	1.0	0	99.5	37.0	0
Chem Chu Yai	21	F	226.0	1.5	1.5	5.0	29.5	94.5	294.5
		3	243.5	1.0	1.0	2.0	58.0	74.0	–
		6	247.0	1.0	1.0	1.5	97.5	52.5	0
		9	265.5	1.0	1.0	0	94.5	35.5	0
DD 95	22	F	230.5	1.0	1.0	5.5	52.5	91.0	270.0
		3	243.5	1.0	1.5	3.5	82.0	91.5	0
		6	264.5	2.0	1.0	2.0	86.0	75.0	9.0
		9	284.0	2.0	1.0	0	99.5	59.0	0.5
Mochi Gomi	23	F	226.0	1.0	1.5	1.0	10.5	81.5	190.5
		3	240.0	1.0	2.0	1.0	62.5	75.5	4.0
		6	245.5	2.0	2.0	1.0	95.0	55.5	34.0
		9	259.5	2.0	1.0	0	100.0	48.0	0
Shimatuki	24	F	248.0	1.0	1.0	1.5	24.5	86.5	90.0
		3	253.0	1.0	1.0	1.0	83.0	83.0	1.0
		6	260.0	1.0	1.0	1.0	100.0	62.5	8.0
		9	267.5	1.5	1.0	0	99.5	45.0	0
Shioji	25	F	242.5	1.0	2.5	2.5	0	69.0	844.5
		3	255.0	1.0	3.0	1.0	16.0	66.0	306.5
		6	262.0	1.0	2.5	1.0	81.0	58.0	73.5
		9	274.0	2.0	1.0	0	95.5	47.5	0
Taichung 1	26	F	239.0	1.5	1.0	2.5	11.5	70.0	302.5
		3	260.0	1.0	3.0	2.0	22.0	68.5	294.5
		6	262.0	2.0	2.0	0.5	70.5	46.0	53.5
		9	279.5	1.5	2.0	0	97.0	35.5	0

Table 1. (Continued)

Variety	Entry No. and Treatment[1/]		Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
Taichung 181	27	F	244.5	1.0	2.0	1.5	13.5	89.0	291.0
		3	251.5	1.0	2.5	1.5	60.0	77.0	69.0
		6	264.5	1.0	1.0	0	98.0	57.5	11.0
		9	280.5	1.5	1.0	0	100.0	46.0	0
Tatsumi Mochi	28	F	236.0	1.0	3.0	0	0	61.0	1.5
		3	241.0	2.0	1.0	1.0	81.0	66.0	0
		6	–	–	–	–	–	–	–
		9	–	–	–	–	–	–	–
IR 442-2-58	29	F	250.0	2.0	2.0	1.0	6.5	78.5	460.0
		3	263.0	2.0	3.0	1.5	26.0	69.5	298.0
		6	278.0	2.0	2.0	0.5	46.5	55.5	60.5
		9	288.0	2.0	2.0	0	86.5	53.0	34.5
IR 789-63-1-1-1-1-2	30	F	255.0	1.5	3.0	1.5	2.0	73.5	723.5
		3	271.0	1.5	3.0	1.5	60.5	57.5	111.0
		6	284.5	2.0	2.0	0	94.5	49.0	0
		9	–	–	–	–	–	–	–
IR 944-85-1-2-2-2-2	31	F	244.5	1.0	2.5	3.0	15.0	75.5	740.5
		3	256.0	1.0	2.0	0.5	35.5	61.5	286.0
		6	249.0	1.0	2.5	0.5	79.5	59.0	36.0
		9	281.0	2.0	2.0	0	100.0	40.5	0
IR 944-93-2-1-2-2	32	F	244.5	1.0	2.5	2.0	0	68.5	470.5
		3	255.0	1.0	2.0	2.0	23.5	63.0	321.5
		6	265.0	1.0	2.5	1.0	61.0	59.0	82.5
		9	267.0	1.5	2.0	0	100.0	40.5	0
IR 1108-3-5-3-2	33	F	243.5	1.0	2.0	1.5	12.0	71.0	384.5
		3	251.5	1.0	3.0	0.5	33.0	57.0	36.0
		6	260.5	1.0	2.5	1.0	47.5	50.5	138.5
		9	274.0	2.0	1.0	0	96.5	40.0	0
IR 1168-24-2-1-3-1	34	F	250.0	1.0	2.0	0.5	17.0	76.0	523.0
		3	262.0	1.0	2.0	2.0	22.5	70.0	399.5
		6	262.0	1.0	1.0	0.5	66.5	61.0	51.5
		9	288.0	2.0	1.0	0	89.0	41.0	0.5
IR 1561-43-2	35	F	242.5	1.0	2.5	2.0	18.0	67.0	393.0
		3	249.5	1.5	2.5	0.5	37.5	55.0	–
		6	264.5	1.5	2.0	0	91.5	47.0	0
		9	290.0	2.0	1.0	0	98.5	31.5	0
IR 1820-210-2	36	F	250.0	1.0	2.5	6.0	29.5	76.5	1086.5
		3	268.0	2.0	2.5	1.0	44.5	57.0	72.5
		6	270.5	2.0	2.5	0	67.0	46.0	–
		9	290.0	2.0	1.0	0	93.0	34.0	0
IR 1857-103-2-2	37	F	250.0	1.0	2.5	3.0	10.0	74.0	464.0
		3	268.0	1.0	3.0	1.5	50.5	57.0	254.5
		6	279.5	1.5	2.5	0.5	69.0	49.0	23.0
		9	–	–	–	–	–	–	–
IR 2004-P7-1-1	38	F	241.0	1.5	3.0	0.5	29.0	76.5	477.0
		3	257.5	2.0	3.0	0.5	48.0	64.5	220.5
		6	271.5	2.0	2.5	0	89.0	53.0	12.0
		9	285.5	2.0	2.0	0	99.5	41.0	0
IR 2016-P2-5-3	39	F	250.0	1.0	2.0	2.0	17.5	74.0	422.5
		3	260.0	1.5	2.0	1.0	44.0	51.0	103.0
		6	270.5	2.0	2.0	0.5	39.0	46.0	40.5
		9	288.0	2.0	1.0	0	98.0	29.0	0

Table 1. (Continued)

Variety	Entry No. and Treatment[1/]		Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
IR 2016-P10-7-3	40	F	236.0	1.0	2.0	1.0	9.5	72.5	436.5
		3	251.5	2.0	2.5	0.5	60.0	63.0	80.5
		6	265.5	2.0	2.0	0	94.0	48.0	0
		9	278.5	2.0	1.5	0.5	84.0	41.5	0
IR 2018-P35-4-3	41	F	250.0	1.0	2.5	1.5	17.0	70.5	364.5
		3	267.0	2.0	2.5	0	21.5	62.0	122.0
		6	279.5	2.0	2.0	0	76.5	49.0	15.0
		9	-	-	-	-	-	-	-
IR 2019-P47-2	42	F	238.5	1.5	2.5	1.0	26.5	76.5	311.5
		3	258.5	2.0	2.5	0.5	46.5	64.5	92.5
		6	260.0	2.0	2.5	0	94.5	56.5	0
		9	289.0	2.0	2.0	0	100.0	40.0	0
IR 2035-269-3-2	43	F	252.5	1.0	3.0	4.0	20.5	72.5	409.0
		3	270.0	2.0	2.0	1.0	45.5	49.5	129.5
		6	281.0	2.0	3.0	0.5	89.0	48.0	6.5
		9	290.0	1.0	2.0	0	88.0	37.0	0
IR 2058-328-1-1	44	F	255.0	1.0	2.5	2.5	5.5	81.0	1075.0
		3	268.0	1.0	2.5	1.0	50.0	66.0	107.0
		6	279.5	2.0	2.0	0	96.5	47.5	0
		9	288.0	2.0	2.0	0	99.5	36.0	0
IR 2058-438-3-2	45	F	256.0	1.5	2.5	2.0	22.5	88.5	772.0
		3	269.0	1.5	3.0	1.0	75.5	57.0	62.0
		6	284.5	2.0	3.0	0	91.5	42.0	0
		9	-	-	-	-	-	-	-
IR 2068-65-3	46	F	251.5	1.0	2.5	4.0	15.5	90.5	387.5
		3	265.5	1.0	3.0	2.0	22.5	79.0	304.0
		6	277.5	1.0	2.5	1.0	74.0	60.0	0
		9	303.0	2.0	1.5	0	97.0	40.5	0
IR 2068-141-3	47	F	241.0	1.0	1.5	2.0	25.0	73.0	421.0
		3	253.0	1.0	1.0	1.0	36.5	66.0	192.0
		6	258.5	1.5	1.0	0.5	47.0	59.5	41.5
		9	276.0	2.0	1.0	0	90.0	43.0	0
IR 2153-43-2-5	48	F	246.0	1.0	2.0	1.0	6.5	66.0	269.5
		3	261.0	1.5	2.0	0.5	67.5	55.5	87.0
		6	269.0	1.5	2.0	0.5	95.0	49.0	5.0
		9	290.0	2.0	1.0	0	100.0	35.0	0
IR 2153-26-3-5	49	F	244.5	1.5	2.0	2.5	18.5	69.0	332.5
		3	257.0	1.0	2.0	1.0	35.0	57.5	181.0
		6	269.0	1.5	1.5	1.0	56.0	56.0	88.0
		9	286.5	2.0	2.0	0	54.0	38.0	0
IV 404-6	50	F	242.0	1.5	2.0	1.5	9.0	71.0	711.0
		3	258.5	1.0	2.5	1.5	25.5	61.0	401.5
		6	264.0	1.5	2.0	1.5	47.0	53.5	96.5
		9	275.0	2.0	2.0	0	90.5	41.0	0

1/ For treatments: F = continuous flood; 3, 6, and 9 = days between irrigations, respectively.
2/ 1 = total panicle exsertion; 2 = partial panicle exsertion (part of panicle enclosed to about 1/3 enclosed in sheath).
3/ 1 = short; 2 = medium; 3 = long; 4 = very long.
4/ To convert yield to kg/hectare (lbs/acre), multiply by a factor of 13.4 (12).

Table 2. Rice irrigation experiment planted on June 11, 1979 (Julian Date 163) at El Centro, California.

Variety	Entry No. and Treatment[1]		Julian Heading Date	Panicle Exsertion[2]	Grain Type[3]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4]
IR 22	1	F	265.5	1.5	2.5	3.0	0	74.0	439.0
		3	276.0	1.5	2.5	1.0	24.5	58.5	14.5
		6	278.0	2.0	3.0	0	45.5	50.0	57.5
		9	289.0	2.0	1.5	0	92.0	38.0	0
IR 26	2	F	265.5	1.5	2.0	2.0	1.5	74.5	292.0
		3	286.5	2.0	2.0	0.5	78.5	54.5	93.5
		6	297.0	2.0	2.0	0	82.5	43.5	83.0
		9	–	–	–	–	–	–	–
IR 28	3	F	250.0	1.0	3.0	4.0	53.0	71.0	173.0
		3	256.0	1.5	2.5	1.0	21.0	61.0	113.5
		6	257.0	1.5	3.0	0	46.0	54.5	83.5
		9	269.0	2.0	2.0	0	98.5	39.5	2.0
IR 2061-464-14-4	4	F	260.0	1.5	3.0	2.5	17.0	75.5	167.0
		3	271.0	2.0	2.5	0.5	25.5	53.0	90.0
		6	278.0	1.5	2.5	0.5	33.0	47.5	55.5
		9	289.0	2.0	2.0	0	78.0	39.0	–
IR 30	5	F	253.0	1.5	2.0	1.0	18.0	67.5	275.0
		3	274.0	1.5	2.5	0	59.0	55.5	70.0
		6	278.5	2.0	2.5	0.5	83.5	51.0	31.0
		9	288.0	2.0	1.5	0	99.5	37.5	0
IV 56	6	F	257.0	2.0	2.5	3.5	12.5	72.5	227.5
		3	263.5	2.0	2.0	1.0	43.0	56.5	132.5
		6	262.0	2.0	3.0	1.0	58.5	54.0	64.0
		9	270.5	2.0	2.0	0.5	96.0	48.5	0
IV 66	7	F	258.5	2.0	1.5	5.0	30.0	58.5	218.0
		3	265.5	2.0	2.0	1.0	45.5	46.5	72.5
		6	265.5	2.0	2.0	0.5	59.5	38.0	30.0
		9	281.0	2.0	1.0	0	99.0	31.0	0
IV 213	8	F	250.0	1.0	1.5	1.0	7.5	70.5	194.0
		3	258.5	1.5	2.0	1.0	15.0	58.0	181.5
		6	261.0	2.0	2.0	1.0	40.5	59.5	109.5
		9	271.5	2.0	1.0	0	96.5	45.5	0.5
IV 237	9	F	258.5	1.0	2.5	0.5	4.0	86.5	264.0
		3	268.0	1.5	2.0	0.5	43.0	61.5	80.0
		6	272.5	1.5	2.0	0.5	42.0	50.0	63.5
		9	281.0	2.0	1.5	0	52.5	41.0	2.5
IV 330-1	10	F	253.0	1.0	2.0	5.0	19.0	71.0	176.0
		3	264.0	2.0	2.0	1.0	18.5	55.5	128.5
		6	268.0	2.0	2.5	1.0	45.5	55.5	119.0
		9	281.0	2.0	2.0	0	97.5	38.0	105.9
IV 404	11	F	257.0	1.0	2.0	5.5	29.5	73.0	388.0
		3	269.0	2.0	2.0	1.5	17.0	57.0	330.5
		6	276.0	2.0	2.5	0.5	51.5	53.5	64.0
		9	288.0	2.0	2.0	0	85.0	45.0	0
Calrose 76	12	F	241.0	1.0	2.0	0.5	6.0	68.5	21.6
		3	250.0	1.0	1.5	0	76.5	55.0	36.5
		6	251.5	1.0	1.5	0	63.5	54.5	13.5
		9	257.5	1.0	1.5	0	85.0	45.0	8.0
Labelle	13	F	246.0	1.0	2.0	0	59.5	88.5	43.0
		3	251.5	1.0	3.0	0	99.0	70.5	2.0
		6	251.5	1.0	2.5	0	87.5	64.0	0
		9	258.5	1.0	3.0	0	100.0	58.5	1.0

Table 2. (Continued)

Variety	Entry No. and Treatment[1]		Julian Heading Date	Panicle Exsertion[2]	Grain Type[3]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4]
Nato	14	F	248.0	1.0	2.0	0	33.0	87.5	108.5
		3	260.0	1.0	2.0	0	92.5	85.5	12.0
		6	265.5	1.0	2.0	0	85.0	71.0	3.0
		9	288.0	1.0	1.0	0	100.0	56.0	0
Lebonnet	15	F	250.0	1.0	3.0	0	59.0	82.0	88.0
		3	253.0	1.0	3.0	0	100.0	68.5	2.5
		6	253.0	1.5	3.0	0	92.5	63.0	0.5
		9	261.0	1.5	3.0	0	100.5	61.0	0
Starbonnet	16	F	258.5	1.0	3.0	0	42.5	96.5	146.0
		3	273.5	1.0	3.0	0	96.5	68.5	4.5
		6	286.5	1.5	3.0	0	99.5	69.5	0
		9	-	-	-	-	-	-	-
Mars	17	F	246.0	1.0	2.0	0	46.0	81.5	202.5
		3	256.0	1.0	2.0	0	54.0	64.5	12.0
		6	262.0	1.0	3.0	0	92.5	55.5	6.0
		9	290.0	1.0	2.0	0	94.0	42.5	0
Newrex	18	F	248.0	1.0	3.0	0	91.5	85.0	67.5
		3	251.5	1.0	3.0	0	100.0	76.5	1.5
		6	253.0	1.0	3.0	0	91.5	64.5	0.5
		9	256.0	2.0	2.5	0	100.0	55.0	0
M101	19	F	236.5	1.0	2.0	1.0	35.0	59.0	268.5
		3	239.0	1.0	2.0	0	53.5	51.5	87.0
		6	237.5	1.5	2.0	0.5	62.5	49.5	26.0
		9	241.0	1.5	1.5	0	86.0	44.0	0
Benkei	20	F	255.0	1.0	1.5	0	46.5	73.0	60.5
		3	255.0	1.0	2.0	0.5	94.5	69.5	24.5
		6	257.0	1.0	2.0	0.5	94.0	62.0	11.0
		9	263.0	1.0	1.5	0	69.5	53.5	0
Chem-chuyai	21	F	253.0	2.0	1.0	2.5	12.5	98.0	230.0
		3	257.0	2.0	2.0	3.0	81.5	95.0	51.5
		6	263.5	1.5	2.0	3.0	95.0	91.5	140.0
		9	282.0	2.0	1.0	0.5	88.0	58.5	0
DD 95	22	F	251.5	1.5	1.0	3.0	45.0	85.0	131.5
		3	255.0	1.5	1.5	2.5	64.0	87.5	87.5
		6	261.0	1.5	2.0	2.5	85.0	80.5	62.0
		9	-	-	-	-	-	-	-
Mochi Gomi	23	F	254.0	1.0	1.2	0	61.0	82.0	71.0
		3	264.0	1.0	2.0	1.0	74.5	61.0	42.5
		6	259.5	2.0	1.5	0	92.0	58.5	33.5
		9	274.0	2.0	1.5	0	89.0	49.5	0
Shima-tuki	24	F	257.5	1.0	1.0	1.0	34.0	78.0	66.5
		3	258.5	1.0	1.5	1.0	89.0	66.0	25.0
		6	260.0	1.0	1.0	0	99.5	68.5	8.5
		9	264.0	1.50	1.0	0	90.0	58.0	0
Shioji	25	F	258.5	1.0	2.5	2.5	8.5	76.5	169.5
		3	277.5	1.5	3.0	0.5	66.0	58.0	125.0
		6	277.5	2.0	2.0	0.5	74.0	55.5	29.5
		9	302.0	2.0	2.0	0	97.0	37.0	0
Taichung 1	26	F	258.5	1.5	2.0	3.5	15.0	76.0	358.0
		3	270.0	1.5	2.5	0	41.5	55.0	114.5
		6	274.0	2.0	2.0	0.5	56.0	56.0	31.0
		9	297.0	2.0	1.0	0	95.0	35.0	0

Table 2. (Continued)

Variety	Entry No.	and Treatment[1/]	Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
Taichung 181	27	F	255.0	1.0	1.0	1.5	11.0	80.0	207.0
		3	263.5	1.0	1.0	1.0	83.0	74.5	38.0
		6	263.5	1.0	1.0	0.5	81.0	72.5	27.5
		9	274.0	1.0	1.0	0	100.0	57.0	0
Tatsumi Mochi	28	F	–	–	–	–	–	–	–
		3	–	–	–	–	–	–	–
		6	277.0	2.0	2.5	0.5	31.5	56.0	0
		9	288.0	2.0	2.0	0	10.0	36.0	0
IR 442-2-58	29	F	260.0	2.0	2.5	3.5	7.5	86.5	372.5
		3	283.0	2.0	3.0	0	48.0	64.0	106.0
		6	339.0	2.0	2.0	0	68.0	49.0	–
		9	304.0	2.0	2.0	0	71.0	46.0	0
IR 789-63-1-1-1-1-2	30	F	274.0	1.5	2.5	1.0	21.0	71.0	420.5
		3	292.5	2.0	3.0	0	80.5	47.5	0
		6	302.0	2.0	2.0	0	80.0	46.0	0
		9	–	–	–	–	–	–	–
IR 944-85-1-2-2-2-2	31	F	262.0	1.0	2.5	3.0	2.0	83.0	322.0
		3	274.0	2.0	2.5	0.5	41.0	58.0	128.0
		6	286.5	2.0	1.5	0	68.0	49.5	27.0
		9	304.0	2.0	1.0	0	96.0	40.0	0
IR 944-93-2-1-2-2	32	F	263.5	1.0	2.5	4.0	0	82.0	233.0
		3	276.0	1.5	3.0	0	26.5	62.0	225.0
		6	283.0	2.0	2.5	0.5	45.5	54.0	48.0
		9	290.0	2.0	2.0	0	100.0	44.0	0
IR 1108-3-5-3-2	33	F	265.5	1.0	2.5	5.5	3.0	76.0	320.0
		3	279.5	2.0	3.0	0	41.5	57.0	72.0
		6	284.5	2.0	2.5	0	50.0	49.0	13.0
		9	264.0	2.0	2.0	2.0	95.5	60.0	0
IR 1168-24-2-1 3-1	34	F	269.0	1.0	1.0	1.5	10.0	83.5	368.5
		3	283.0	1.5	2.0	1.0	47.5	68.5	151.0
		6	290.0	2.0	2.0	0	75.5	50.0	0
		9	–	–	–	–	–	–	–
IR 1561-43-2	35	F	262.0	1.5	3.0	1.5	3.0	69.5	316.0
		3	268.0	1.5	3.0	0.5	60.5	56.0	89.0
		6	271.5	2.0	2.0	0	70.0	49.5	12.0
		9	277.5	2.0	2.0	0	98.0	43.0	0
IR 1820-210-2	36	F	274.0	2.0	3.0	1.0	52.0	75.5	299.5
		3	300.5	2.0	1.5	0	71.5	52.0	0
		6	–	–	–	–	–	–	–
		9	–	–	–	–	–	–	–
IR 1857-103-2-2	37	F	270.0	1.0	3.0	1.0	0.0	83.50	354.3
		3	283.0	2.0	2.0	0	27.0	56.5	90.0
		6	289.0	2.0	2.0	0	76.0	45.5	5.5
		9	–	–	–	–	–	–	–
IR 2004-P7-1-1	38	F	267.0	1.0	3.0	1.0	10.5	81.0	473.5
		3	277.5	2.0	2.5	0	62.0	61.0	36.5
		6	288.0	2.0	2.5	0	88.0	44.5	7.0
		9	290.0	2.0	2.0	0	83.0	50.0	0
IR 2016-P2-5-3	39	F	271.5	1.0	2.5	2.0	67.5	81.0	269.0
		3	286.5	2.0	2.0	0	52.5	53.5	23.0
		6	292.5	2.0	2.0	0	68.0	41.5	57.0
		9	–	–	–	–	–	–	–

Table 2. (Continued)

Variety	Entry No. and Treatment[1/]		Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
IR 2016-P10-7-3	40	F	261.0	1.5	3.0	0.5	22.5	74.0	279.5
		3	268.0	1.5	3.0	0.5	50.0	62.5	105.0
		6	276.0	2.0	2.5	0	66.0	50.5	12.0
		9	284.5	2.0	1.5	0	53.5	41.0	0
IR 2018-P35-4-3	41	F	271.0	1.0	2.5	4.0	13.5	79.0	221.5
		3	288.0	2.0	2.0	0	63.0	52.0	-
		6	304.0	2.0	-	0	93.0	49.0	0
		9	-	-	-	-	-	-	-
IR 2019-P47-2	42	F	261.0	1.0	3.0	0.5	60.0	79.0	298.5
		3	286.5	2.0	3.0	0	61.5	57.0	23.5
		6	271.5	2.0	2.0	0	74.0	54.0	18.0
		9	288.0	2.0	1.5	0	99.0	43.0	0
IR 2035-269-3-2	43	F	276.0	1.5	3.0	1.5	14.5	73.0	380.0
		3	288.0	2.0	2.0	0	46.5	45.5	0
		6	290.0	2.0	2.0	0	44.5	49.0	0
		9	-	-	-	-	-	-	-
IR 2058-328-1-1	44	F	274.0	1.0	3.0	2.0	2.0	73.5	679.5
		3	297.0	2.0	2.5	0	88.0	49.0	0
		6	304.0	2.0	2.0	0	81.0	42.0	0
		9	-	-	-	-	-	-	-
IR 2058-438-3-2	45	F	274.0	1.5	3.0	1.5	55.0	87.0	675.0
		3	289.0	2.0	2.5	0	76.5	46.5	0
		6	289.0	2.0	3.0	0	98.5	50.5	0
		9	-	-	-	-	100.0	-	0
IR 2068-65-3	46	F	274.0	1.0	3.0	5.0	39.0	92.0	687.5
		3	290.0	2.0	2.0	0	48.0	63.0	3.0
		6	283.0	1.5	1.5	0	93.0	50.0	0
		9	-	-	-	-	-	-	-
IR 2068-141-3	47	F	260.0	1.0	2.0	3.5	1.5	87.0	324.0
		3	276.0	1.5	1.5	0.5	56.5	66.5	80.0
		6	279.5	1.5	1.5	0	76.0	56.5	28.5
		9	289.0	2.0	1.5	0	99.0	44.0	0
IV 404-6	48	F	262.0	1.0	2.0	6.5	4.0	76.0	283.5
		3	276.0	2.0	2.0	0	52.0	58.0	37.5
		6	284.5	2.0	2.0	0	91.5	42.0	0
		9	-	-	-	-	-	-	-
IR 2153-26-3-5	49	F	264.0	1.5	2.5	2.5	4.0	75.5	298.5
		3	274.0	2.0	2.0	0	47.5	56.5	61.0
		6	277.5	2.0	2.5	0.5	49.5	53.0	50.5
		9	297.0	2.0	2.0	0	95.0	40.0	0
IV 404-6	50	F	256.0	1.0	2.5	6.0	20.0	71.0	287.5
		3	272.5	1.5	2.5	1.5	31.5	52.5	146.0
		6	279.5	2.0	2.5	0.5	60.0	62.0	82.0
		9	289.0	2.0	1.5	0	69.5	44.0	8.0

1/ For treatments; F = continuous flood; 3, 6, and 9 = days between irrigations, respectively.
2/ 1 = total panicle exsertion; 2 = partial panicle exsertion (part of panicle enclosed to about 1/3 enclosed in sheath).
3/ 1 = short; 2 = medium; 3 = long; 4 = very long.
4/ To convert yield to kg/hectare (lbs/acre), multiply by a factor of 13.4 (12).

Table 3. Rice irrigation experiment planted on July 11, 1979 (Julian Date 193) at El Centro, California.

Variety	Entry No. and Treatment[1/]		Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
IR 22	1	F	286.5	2.0	2.5	0	24.0	67.0	192.5
		3	303.0	2.0	2.5	0	99.0	43.5	0
		6	300.5	2.0	1.5	0	100	37.5	0
IR 26	2	F	291.5	2.0	2.0	0	46.5	66.0	105.0
		3	–	–	–		–	–	–
		6	–	–	–		–	–	–
		9	–	–	–		–	–	–
IR 28	3	F	269.0	1.0	3.0	5.0	6.0	66.0	133.5
		3	279.0	1.5	3.0	1	27.0	50.5	65.0
		6	281.0	1.0	3.0	1	49.0	49.5	49.5
		9	286.5	2	3.0	0	83.0	42.5	18.5
IR 2061-464-14-4	4	F	283.0	2.0	3.0	0.5	19.5	63.0	66.0
		3	297.0	2.0	3.0	0	60.5	38.0	0
		6	300.5	2.0	2.0	0	86.5	34.5	0
		9	–	–	–	–	–	–	–
IR 30	5	F	270.0	1.5	2.0	3	17.0	66.5	259.0
		3	284.5	2.0	2.0	0	79.5	49.0	5.0
		6	286.5	2.0	2.0	0	72.5	45.5	4.0
		9	297.0	2.0	2.0	0	100.0	37.0	0
IV 56	6	F	272.5	2.0	3.0	4.5	27.5	67.0	163.0
		3	281.0	2.0	2.5	0.5	66.0	48.5	28.5
		6	281.0	2.0	2.5	0.5	75.0	62.0	22.5
		9	277.0	2.0	1.5	0	95.0	46.5	0
IV 66	7	F	270.5	2.0	2.0	1.5	34.5	53.0	119.0
		3	281.0	2.0	2.0	0.5	97.0	41.5	2.0
		6	276.0	2.0	1.0	0.5	83.0	40.5	9.0
		9	281.0	2.0	2.0	0	97.0	34.5	0
IV 213	8	F	271.5	1.50	2.0	2.0	11.0	77	272.0
		3	290.0	2.0	2.0	0	91.5	0	47.5
		6	296.0	2.0	2.0	0	91.5	0	44.0
		9	–	–	–	–	–	–	–
IV 237	9	F	277.5	1.5	2.0	1.5	11.5	61.0	163.0
		3	289.0	2.0	2.5	0	74.0	45.5	9.5
		6	297.0	2.0	2.0	0	74.5	40.0	0
		9	279.5	1.5	2.0	0	78.0	44.5	0
IV 330-1	10	F	276.0	1.5	2.0	3.5	28.0	69.0	251.0
		3	304.0	2.0	2.5	0	81.5	38.0	0
		6	300.5	2.0	2.5	0	93.5	40.0	0
		9	304.0	2.0	2.0	–	96.5	36.0	0
IV 404	11	F	276.0	2.0	2.5	3.0	22.5	64.5	216.5
		3	278.0	2.0	3.0	1.0	70.5	43.0	25.0
		6	278.0	2.0	3.0	1.0	28.0	39.0	15.5
		9	281.0	2.0	2.5	0.5	68.0	45.5	17.0
Calrose 76	12	F	256.0	1.0	2.0	0.5	28.0	69.0	117.0
		3	264.5	1.0	2.0	0	47.0	55.0	33.0
		6	265.5	1.0	2.0	0.5	92.0	43.5	23.0
		9	268.0	1.0	1.5	0	90.0	50.0	6.0
Labelle	13	F	263.0	1.0	3.0	0	58.5	92.0	78.5
		3	275.0	1.0	3.0	0	91.5	83.5	4.5
		6	269.0	1.0	3.0	0	100.0	70.5	2.5
		9	270.0	1.0	3.0	0	100.0	64.5	1.0

Table 3. (Continued)

Variety	Entry No. and Treatment[1/]		Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
Nato	14	F	271.0	1.0	2.0	0	65.5	91.0	135.0
		3	289.0	1.5	2.0	1.0	91.0	75.0	4.5
		6	292.5	1.5	2.5	0	92.0	63.5	0
		9	-	-	-	-	-	-	-
Lebonnet	15	F	265.5	1.0	3.0	0	58.0	87.0	119.5
		3	271.5	1.5	3.0	0	82.5	70.0	6.0
		6	270.0	1.0	3.0	0	100.0	71.5	5.5
		9	272.5	2.0	3.0	0	100.0	61.0	0
Star-bonnet	16	F	288.0	1.0	3.0	0	35.0	87.0	119.5
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
Mars	17	F	270.0	1.0	2.0	0.5	29.5	79.0	120.5
		3	283.0	1.0	2.5	0	93.0	68.0	6.5
		6	288.0	2.0	2.0	0	93.0	54.5	1.0
		9	-	-	-	-	-	-	-
Newrex	18	F	269.5	1.0	3.0	0	67.5	88.5	45.5
		3	271.5	1.0	3.0	0	97.5	76.0	177.5
		6	268.0	1.0	3.0	0	100.0	70.5	0.5
		9	270.0	2.0	3.0	0	100.0	62.5	6.0
M101	19	F	251.5	1.0	1.5	0.5	29.0	64.5	197.5
		3	259.5	1.0	2.0	0	78.5	56.5	50.0
		6	258.5	1.0	2.0	0	77.5	51.5	37.0
		9	258.5	1.0	2.0	0	98.5	46.0	0
Benkei	20	F	264.0	1.0	1.5	1.0	40.0	63.0	22.5
		3	268.0	1.0	2.0	1.0	93.0	62.0	21.5
		6	267.0	1.0	1.5	0.5	87.5	66.5	13.5
		9	269.0	1.0	1.0	0	100.0	61.0	0
Chem-chuyai	21	F	270.0	1.0	2.0	5.0	14.5	94.5	253.0
		3	281.0	1.5	1.5	2.0	82.0	72.5	13.0
		6	278.0	2.0	1.0	1.0	94.0	48.0	3.5
		9	284.5	2.0	1.5	1.0	99.5	79.0	0
DD 95	22	F	265.5	1.0	2.0	4.5	17.0	92.0	120.5
		3	274.5	1.5	2.0	2.0	78.0	71.0	72.0
		6	274.0	1.5	1.5	2.5	69.5	80.0	62.5
		9	278.0	2.0	1.5	2.5	77.0	74.5	44.5
Mochi Gomi	23	F	271.5	1.5	2.0	2.5	50.0	75.5	72.5
		3	274.5	1.0	2.0	1.5	73.5	66.5	13.0
		6	281.0	1.0	1.5	1.0	80.5	74.0	9.0
		9	288.0	2.0	1.0	0	98.5	53.0	0
Shima-tuki	24	F	268.0	1.0	1.0	0.5	29.0	60.0	17.0
		3	269.0	1.0	1.5	1.0	61.0	60.5	10.0
		6	268.0	1.0	1.5	1.0	89.5	62.5	23.0
		9	272.5	1.0	1.0	1.0	96.0	58.0	0
Shioji	25	F	288.0	2.0	2.5	1.5	33.5	68.0	235.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
Taichung 1	26	F	288.0	2.0	2.5	1.5	35.5	57.5	50.5
		3	304.0	2.0	1.0	0	85.0	42.0	0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-

Table 3. (Continued)

Variety	Entry No. and Treatment1/		Julian Heading Date	Panicle Exsertion2/	Grain Type3/	Percent Lodging	Percent Blanking	Height in cm	Yield in gm4/
Taichung 181	27	F	268.0	1.0	1.0	1.0	9.5	70.5	74.0
		3	281.0	1.0	2.0	0.5	81.5	71.5	23.0
		6	274.0	1.0	1.0	1.0	68.5	63.0	9.5
		9	284.5	1.0	1.0	0.5	94.0	54.0	0
Tatsumi Mochi	28	F	276.0	2.0	2.5	1.5	18.5	69.5	109.5
		3	299.5	2.0	2.5	0	78.5	39.5	0
		6	300.5	2.0	2.5	0	95.5	40.5	0
		9	-	-	-	-	-	-	-
IR 442-2-58	29	F	286.5	2.0	3.0	1.0	14.0	77.0	325.5
		3	302.0	2.0	3.0	0	99.0	40.0	0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 789 63-1-1 1-1-2	30	F	288.0	2.0	3.0	0.5	57.5	73.5	166.5
		3	297.0	2.0	2.0	0	88.0	42.0	0
		6	311.0	2.0	2.5	0	100.0	36.5	0
		9	-	-	-	-	-	-	-
IR 944-85-1-2-2-2-2	31	F	286.5	2.0	3.0	1.5	21.0	71.5	215.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 944-93-2-1-2-2	32	F	285.0	1.5	3.0	2.0	37.0	67.5	207.5
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 1108-3-5-3-2	33	F	288.0	2.0	2.5	0	55.0	59.0	93.5
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 1168-24-2-1-3-1	34	F	292.5	2.0	2.0	0	59.0	55.5	91.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 1561-43-2	35	F	281.0	2.0	3.0	0.5	10.0	62.5	235.5
		3	296.0	2.0	3.0	0	94.0	46.0	0
		6	292.5	2.0	2.5	0	94.5	42.5	0
		9	297.0	2.0	2.0	0	93.5	42.0	0
IR 1820-210-2	36	F	297.0	2.0	2.5	0	64.5	62.5	21.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 1357-103-2-2	37	F	289.0	2.0	2.5	0	42.0	62.5	142.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2004-P7-1-1	38	F	291.5	2.0	3.0	0	34.0	65.0	55.5
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2016-P2-5-3	39	F	296.0	2.0	2.0	0	67.0	55.0	66.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-

Table 3. (Continued)

Variety	Entry No. and Treatment[1/]		Julian Heading Date	Panicle Exsertion[2/]	Grain Type[3/]	Percent Lodging	Percent Blanking	Height in cm	Yield in gm[4/]
IR 2016-P10-7-3	40	F	278.0	1.5	3.0	0	21.0	71.0	233.5
		3	289.0	2.0	3.0	0	73.5	45.0	-
		6	290.0	2.0	0	0	92.0	37.0	0
		9	302.0	2.0	0	0	100.0	37.0	0
IR 2018-P35-4-3	41	F	296.0	2.0	2.0	0	80.0	67.5	45.5
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2014-P47-2	42	F	277.5	2.0	2.5	0	28.0	66.5	62.5
		3	297.0	2.0	2.0	0	77.5	49.0	100.0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2035-269-3-2	43	F	300.5	2.0	2.5	0	74.0	53.0	14.5
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2058-328-1-1	44	F	283.0	2.0	3.0	1.0	32.0	70.0	215.0
		3	300.5	2.0	3.0	0	98.0	40.0	0
		6	311.0	2.0	2.0	0	96.5	41.0	0
		9	-	-	-	-	-	-	-
IR 2058-738-3-2	45	F	290.0	2.0	3.0	0	66.0	67.5	52.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2068-65-3	46	F	300.5	2.0	2.0	0	86.0	10.0	5.0
		3	-	-	-	-	-	-	-
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2068-141-3	47	F	283.0	2.0	1.5	0.5	33.0	73.0	158.0
		3	304.0	2.0	2.0	0	79.0	44.0	0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IV 404-6	48	F	286.5	2.0	3.0	0	38.0	67.5	203.5
		3	302.0	2.0	2.0	0	97.0	46.0	0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IR 2153-26-3-5	49	F	284.5	2.0	2.0	1.5	46.0	66.0	217.0
		3	297.0	2.0	2.0	0	99.5	39.0	0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-
IV 404-6	50	F	284.5	2.0	3.0	0	28.0	61.0	193.5
		3	297.0	2.0	3.0	0	87.5	39.0	0
		6	-	-	-	-	-	-	-
		9	-	-	-	-	-	-	-

1/ For treatments; F = continuous flood; 3, 6, and 9 = days between irrigations, respectively.
2/ 1 = total panicle exsertion; 2 = partial panicle exertion (part of panicle enclosed to about 1/3 enclosed in sheath).
3/ 1 = short; 2 = medium; 3 = long; 4 = very long.
4/ To convert yield to kg/hectare (lbs/acre), multiply by a factor of 13.4 (12).

Table 4. Average soil salinity measurements in EC of mmho/cm before and after irrigations for three irrigation and planting date treatments at El Centro, California, in 1980.

Irrig. Treat-ment	Plant-ing Date	30-cm Soil Depth		Difference	30 to 60-cm Soil Depth		Difference
		Before Irrigation	After Irrigation	mmho/cm and %	Before Irrigation	After Irrigation	mmho/cm and %
Flood	4/17	4.47	3.01	1.46 33%	4.85	4.33	.52 11%
3 day	4/17	3.99	1.80	2.19 55%	3.39	2.00	1.39 41%
6 day	4/17	3.09	1.77	1.32 43%	2.76	2.66	.10 4%
Flood	5/15	3.27	2.15	1.12 34%	3.24	2.57	.67 21%
3 day	5/15	2.65	1.45	1.20 45%	2.49	1.54	.95 38%
6 day	5/15	2.26	1.39	.87 38%	2.20	1.53	.67 30%
Flood	6/17	5.86	2.86	3.00 51%	5.20	3.24	1.96 38%
3 day	6/17	3.36	1.55	1.81 54%	2.69	1.44	1.25 45%
6 day	6/17	3.19	1.46 54%	1.73	2.80	1.67	1.13 40%

Table 5. Germination dates, temperature during germination, heading dates, and harvest dates for 3 planting dates at Yuma, Arizona, 1979.

Factor		Planting Dates 9 May	30 May	20 June
Julian Planting Date		129	150	171
Julian Germination Date		137	156	176
Air Temperature (°C) During Germination	Avg. Max.	33	36	39
	Avg. Min.	14	17	18
Average Julian Heading Date				
	(1) Calrose 76	228	248	254
	(2) Nato	222	248	254
	(3) Labelle	221	248	254
	(4) Labonnet	221	248	254
Estimated Julian Harvest Date[1/]		305	319	335
Growing Season Length		176	169	164

1/ Actually all plots harvested on 1 December, but records were kept when the earlier planting dates could have been harvested.

Table 6. Summary of seasonal irrigation water applied, precipitation, and pan evaporation for 3 irrigation treatments, and 3 planting dates at Yuma, Arizona, 1979.

Factor	Irrigation Treatment 1/	Planting Dates 9 May	30 May	20 June
Number of Irrigations	2/wk	41	33	28
	1/wk	27	21	19
	10 days	24	18	14
Estimated Seasonal Irrigation Water Applied (cm) 2/	2/wk	258	208	176
	1/wk	170	132	120
	10 days	151	113	88
Seasonal Precipitation (cm)	All Irrig. Trts.	4.5	3.6	3.6
Seasonal Total Water Applied (cm)	2/wk	263	212	180
	1/wk	175	136	124
	10 days	156	117	92
Seasonal Pan Evaporation (cm)	All Irrig. Trts.	198	182	180

1/ Irrigation water was applied either twice a week, once a week, or every 10 days.

2/ Based on an average irrigation size of 6.3 cm (2.5 inches).

Table 7. Summary of rice yield (mean of 4 replicates) for 3 planting dates and 2 selected varieties at Yuma, Arizona, 1979.

Irrigation Treatment 1/	Planting Dates: 9 May	30 May	20 June
		kg/hectare	
		Calrose 76	
2/wk	1444	2176	1326
1/wk	115	530	524
10 days	23	140	146
		Labelle	
2/wk	1144	749	491
1/wk	64	170	175
10 days	274	– *	101

1/ Irrigation water was applied either twice a week, once a week, or every 10 days.
* Negligible yield and considerable variability.

Table 8. Average and range of leaf analysis on rice for 3 growth stages and grain nutrient analysis at harvest for 3 planting dates at Yuma, Arizona, 1979.

Planting Date	Leaf Analysis - Days Since Planting 1/									Nutrient Analysis for Harvested Rice 1/				
	50			65			80							
	N	PO_4-P	Fe	N	PO_4-P	Fe	N	PO_4-P	Fe	N*	Fe	Mn	Zn	Cu
	(%)	-(ppm)-		(%)	-(ppm)-		(%)	-(ppm)-		(%)	---------- (ppm) --------			
9 May avg.	3.3	1500	84	2.9	1225	125	2.7	925	130	2.7	115	61	16	16
Range-low	2.9	1200	38	2.6	1050	62	2.5	850	110	2.4	96	38	12	10
high	3.6	1800	105	3.2	1450	115	3.0	1200	160	2.9	156	110	20	22
30 May avg.	3.4	1100	102	3.1	975	120	2.9	725	135	3.0	98	66	10	15
Range-low	3.2	950	72	2.8	850	94	2.6	600	118	2.8	76	38	8	8
high	3.9	1300	120	3.5	1100	138	3.2	850	156	3.4	118	112	12	21
20 June avg.	3.7	1425	94	3.4	775	115	3.1	595	142	3.0	85	85	11	18
Range-low	3.0	1250	68	2.6	700	84	2.5	450	112	2.6	62	64	6	12
high	4.4	1800	108	4.1	1000	130	3.7	800	160	3.3	101	112	16	26

1/ Includes all 4 varieties - Calrose 76, Nato, Labelle, and Labonnet.
* Percent Protein = N x 6.25.

Table 9. Soil and plant tissue analysis guide for California rice production in terms of nitrogen, phosphorous, potassium, and zinc. 1/

Soil Analysis			Plant Analysis - Recently Mature Leaves 2/						
				Mid-Tillering		Maximum Tillering		Panicle Initiation	
Element	Soil Test Method	Critical Value	Element	Critical Value	Adequate Range	Critical Value	Adequate Range	Critical Value	Adequate Range
Nitrogen	Not reliable		N (%)	3.0	3.0-4.0	28	2.8-3.6	2.6	2.6-3.2
Phosphorous	$NaHCO_3$	6 ppm PO_4-P	PO_4-P (ppm)	1000	1000-1800	800	800-1800	800	800-1800
Potassium	NH_4Ac	60 ppm K	K(%)	1.4	1.4-2.8	1.2	1.2-2.4	1.0	1.0-2.2
Zinc	DTPA	0.5 ppm Zn	Zn	20	22-80	15	15-25	15	15-25

1/ Miller, M. D., M. L. Peterson, D. S. Mikkelsen, D. M. Brandon, C. M. Week, J. F. Williams, and R. S. Baskett. 1973. Rice production in California. University of California Bull. No. 75-6E/2236, Cooperative Extension, Berkeley, CA 94720.

2/ Analysis on dry weight basis. Kieldahl N, 2% $HAcPO_4$-P, and K.

Table 10. Germination dates, temperatures during germination, heading dates, and harvest dates for 6 planting dates at Yuma, Arizona, 1980.

Factor	Planting Dates: 29 Feb	19 Mar	16 Apr	14 May	16 Jun	8 Jul
Julian Planting Date	60	80	107	136	168	190
Julian Germination Date	85	100	119	142	172	195
Air Temperature (°C) during Germination						
Avg. Max.	24	25	32	34	41	39
Avg. Min.	9	9	12	16	19	22
Average Julian Heading Date 1/	214	216	217	222	246	259
Julian Harvest Date	296	296	296	No*	No**	No**
Growing Season Length in Days	236	216	189	--	--	--

1/ Average heading date for Calrose 76, Labelle, IV 213, IR 22, and IR 1108-3-5-3-2 varieties, while M101 was considerably earlier and more erratic in panicle development.
* Limited harvest data taken because of poor stands caused by large weed infestations.
** Limited harvest data taken because of poor seed development caused by blanking in late September and early October.

Table 11. Summary of seasonal irrigation water applied, precipitation, and pan evaporation for 3 irrigation treatments and 6 planting dates at Yuma, Arizona, 1980.

Factor	Irrigation Treatment[1/]	Planting Dates: 29 Feb	19 Mar	16 Apr	14 May	16 Jun	8 Jul
Number of Irrigations	2/wk	42	38	34	37	34	24
	1/wk	30	28	23	23	24	18
	10 days	27	25	21	23	20	15
Seasonal Irrigation Water Applied (cm)	2/wk	258	251	254	246	226	162
	1/wk	183	192	174	158	161	126
	10 days	168	162	157	157	140	108
Average Irrigation Size (cm)	2/wk	6.2	6.2	7.5	5.7	6.6	6.7
	1/wk	6.1	6.8	8.3	6.9	6.7	7.0
	10 days	6.2	6.5	7.5	6.8	7.0	7.2
Range of Irrigation Water Applied (cm)	2/wk	3.4-7.7	5.2-8.1	4.8-14.5	5.2-8.6	5.0-10.0	5.2-8.8
	1/wk	3.6-7.9	4.3-10.9	4.3-12.7	5.2-8.6	5.0-9.5	5.0-8.8
	10 days	2.9-8.4	5.2-8.6	4.5-11.5	5.2-9.5	5.2-9.3	5.7-8.8
Seasonal Precipitation (cm)	All Irrig. Trts.	1.8	1.0	0.9	0.4	0.4	0.4
Seasonal Total Water Applied (cm)	2/wk	260	252	255	246	226	162
	1/wk	185	193	175	158	161	126
	10 days	170	163	158	157	140	108
Seasonal Pan Evaporation	All Irrig. Trts.	244	231	208	195	157	130

1/ Irrigation water was applied either twice a week, once a week, or every 10 days.

Table 12. Average and range of leaf analysis on rice for 3 growth stages and grain nutrient analysis at harvest for 6 planting dates at Yuma, Arizona, 1980.

Planting Date	Leaf Analysis - Days Since Planting 50			65			80			Composite of 50, 65 & 80				Nutrient Analysis for Harvested Rice 1/						
	N	PO_4-P	K	N	PO_4-P	K	N	PO_4-P	K	Fe	Zn	Mn	Cu	N*	K	P	Fe	Mn	Zn	Cu
(ppm)——→	(%)	(ppm)	(%)	(%)	(ppm)	(%)	(%)	(ppm)	(%)	——(ppm)——				——(%)——			——(ppm)——			
29 Feb																				
avg.	4.7	1590	2.1	4.0	1240	1.8	3.7	1040	1.5	228	40	95	16	2.8	1.9	0.22	124	28	45	25
Range-																				
low	3.6	1000	1.6	3.0	900	1.4	2.8	825	1.1	140	28	40	10	2.3	1.1	0.14	108	23	32	12
high	5.5	2100	2.4	4.9	1600	2.2	4.6	1300	2.0	330	56	121	19	3.4	2.5	0.42	164	36	68	36
19 Mar																				
avg.	3.8	1130	2.3	3.4	990	2.0	2.8	1070	1.6	206	47	24	18	3.6	1.6	0.32	141	24	54	21
Range-																				
low	3.3	850	2.0	3.0	800	1.7	2.4	900	1.4	134	32	17	11	3.2	1.2	0.21	110	18	30	15
high	4.4	1550	2.5	3.8	1200	2.3	3.1	1225	1.8	322	72	30	34	3.9	2.8	0.50	216	32	73	28
16 Apr																				
avg.	3.6	1130	2.0	4.2	1160	2.1	3.6	1180	2.0	170	44	28	16	3.4	1.9	0.28	141	23	46	16
Range-																				
low	3.0	850	1.7	3.4	650	2.0	3.1	900	1.7	118	26	20	11	2.8	1.7	0.26	118	18	40	14
high	4.4	1450	2.3	4.8	1550	2.3	4.1	1550	2.3	280	52	32	24	4.2	2.4	0.32	162	30	54	18
14 May																				
avg.	4.7	990	2.2	4.4	950	1.9	3.4	1100	1.8	158	38	32	16	3.3	2.3	0.26	164	19	64	18
Range-																				
low	4.1	825	2.0	4.1	600	1.7	3.2	825	1.4	112	28	24	11	3.0	2.0	0.16	144	18	65	14
high	5.2	1700	2.4	5.0	1450	2.2	3.8	1800	2.1	248	52	42	12	3.7	2.7	0.36	190	20	78	23
16 Jun																				
avg.	4.8	1180	1.9	4.5	1240	2.1	3.9	1270	2.2	170	36	27	17	-**	-	-	-	-	-	-
Range-																				
low	4.0	750	1.4	4.0	700	1.8	3.5	600	2.0	126	26	20	11							
high	5.6	2400	2.2	5.6	2325	2.4	4.6	2900	2.6	254	48	34	26							
8 Jul																				
avg.	3.8	1280	1.7	4.4	1400	2.1	3.5	1270	1.8	213	28	20	25	-	-	-	-	-	-	-
Range-																				
low	3.1	1100	1.3	4.2	1000	1.7	3.2	850	1.4	142	18	16	20							
high	5.2	1500	2.2	5.4	1850	2.4	3.9	1900	2.0	280	34	26	36							

1/ Representative sample available only for first 4 planting dates and IR 22, IV 213, and IR 1103-3-5-3-2 varieties.
* Percent protein = N x 6.25.
** Limited quantity of rice harvested.

Table 13. Summary of rice yields and grain weight (mean of 4 replicates for 6 planting dates and 3 selected varieties at Yuma, Arizona, 1980.

Irrigation Treatment1/	Planting Dates 29 Feb	19 Mar	16 Apr	14 May	16 Jun	8 Jul
	kg/hectare (gms/500 grains)					
	IR 22					
2/wk	4037 (9.4)	6957 (9.7)	4519 (9.6)	3929 (9.6)	-----*	----
1/wk	5742 (9.5)	5324 (9.3)	1705 (10.0)	----	----	----
10 days	2845 (9.4)	2890 (9.0)	2874 (9.8)	----	----	----
	IV 213					
2/wk	3413 (9.8)	4946 (10.6)	5518 (10.2)	3734 (11.0)	----	----
1/wk	3043 (9.7)	2295 (9.5)	----	----	----	----
10 days	----	1676 (9.6)	----	----	----	----
	IR 1108-3-5-3-2					
2/wk	5380 (10.1)	6670 10.5)	5178 11.6	4346 (10.7)	----	----
1/wk	6475 (10.8)	6406 (10.5)	808 (10.0)	----	----	----
10 days	2447 (10.4	2745 (9.2)	----	----	----	----

1/ Irrigation water was applied either twice a week, once a week, or every 10 days.
* Negligible yield and considerable variability.

Table 14. Effect of applying sulfuric acid on the soil pH, electrical conductivity, and soluble sodium during the rice growing season at Safford, Arizona, 1980. 1/

Depth of Soil Sampling (cm)	Planting Dates: 9 May — Days Since Planting	pH	EC (mmhos/cm)	Na (mg/l)	5 June — Days Since Planting	pH	EC (mmhos/cm)	Na (mg/l)
0-7.5	0*	8.2	2.2	500	0*	8.0	6.9	1570
7.5-15		7.1	4.2	780		8.1	4.8	1130
15-30		8.0	3.8	670		7.3	3.2	680
0-7.5	22	7.2	5.6	1080	16	6.7	5.0	1150
7.5-15		7.8	4.0	900		7.9	4.3	1060
15-30		7.1	2.8	680		7.7	3.8	610
0-7.5	99	5.9	4.8	710	72	6.9	4.5	700
7.5-15		7.6	5.1	905		7.8	3.4	560
15-30		7.2	5.2	1040		7.9	2.8	520
0-7.5	220**	8.1	2.3	550	193**	7.7	3.4	610
7.5-15		7.7	2.4	600		7.9	3.2	720
15-30		7.5	5.1	1400		-	-	-

1/ Averaged for the three irrigation treatments.
* Before applying sulfuric acid and planting rice.
** After rice harvesting.

Table 15. Summary of rice yield and grain weight for Calrose 76 variety and 2 planting dates at Safford, Arizona, 1980.

Irrigation Treatment 1/	Planting Dates 2/ 9 May	5 June
	kg/hectare (gms/500 grains)	
2/wk	2393 (11.1)	2500 (11.4)
1/wk	3590 (11.2)	2654 (10.2)
10 days	2657 (10.3)	2711 (10.8)

1/ Irrigation water was applied either twice a week, once a week, or every 10 days.
2/ First and second planting dates were harvested on 29 October and 4 December, respectively.

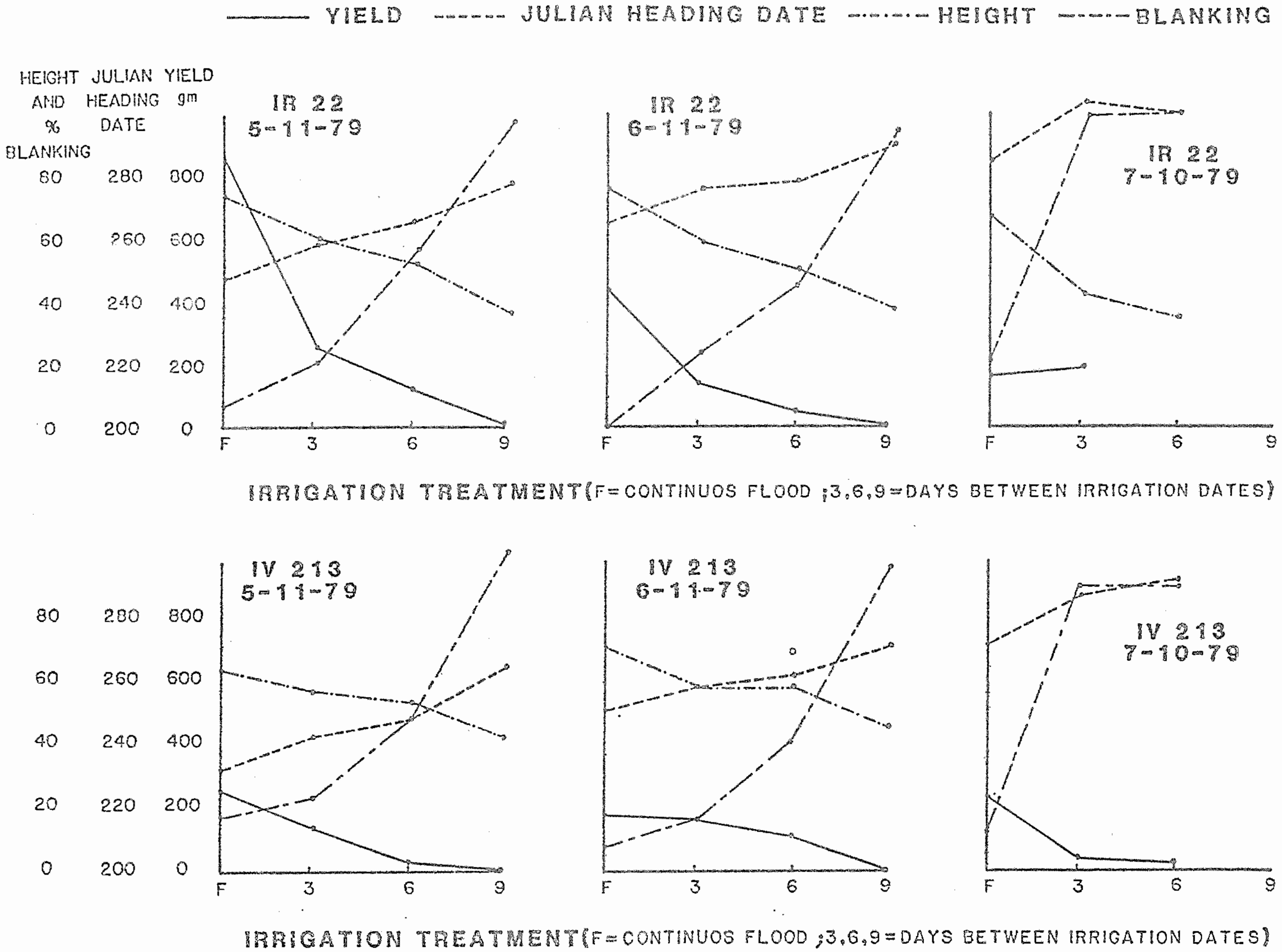

Figure 1. Effects of three irrigation treatments at three planting dates for IR 22 and IV 213 rice varieties at El Centro, California, 1979.

TITLE: SURFACE IRRIGATION AUTOMATION

NRP: 20740 CRIS WORK UNIT: 5510-20740-004

INTRODUCTION:

Surface irrigation, because of its low water distribution energy requirements compared to pressurized systems, merits intensified attention. If, however, surface irrigation techniques are to be used successfully in the future they likely must be operated automatically. Automation, as an irrigation management tool, assures more precise control of the quantity of water applied. It can result in water savings and crop yield improvement by minimizing prolonged inundation time and crop scald. In the future, reduced farm labor requirements may be as important as improved irrigation water control.

Most of the work at this location to date has been associated with large flow rate (large gates) and adaptations to automatic controls to existing gates. Future research and demonstrational studies will include design of equipment for small farms with an emphasis on development of gates that are suited to automation. In all cases, the devices used must be simple to operate, reliable and economical. Installation procedures will be developed and maintenance requirements of the systems will be determined.

OBJECTIVES:

To provide to surface irrigation, convenient automated flow control systems that will efficiently use water and energy resources. The systems must be cost-effective and reliable enough to achieve widespread adoption on both large and small farms which use a variety of water supply sources and sizes.

REVIEW OF LITERATURE:

Automatic irrigation gate operation, as used in this outline, means a series of gates or water turnout devices that are operated remotely to divert water into basins or borders from a canal common to all basins. The actuation is according to some predetermined schedule which may be either time, time/distance (length), or water-quantity controlled.

Pneumatic valve systems, hydraulically-controlled butterfly valves, pneumatically-operated lift-gates, reinforced butyl rubber dams, hydraulic pressure gates, and drop gates all have been or are being evaluated for automating surface irrigation systems. We have used automated control equipment successfully for nearly 6 years on two sites. The pneumatic controls and actuators have been featured on lift-gates and on concrete ports for surface distribution systems.

At the request of the Soil Conservation Service, the first cost-shared automated irrigation system was designed and installed as part of the on-farm irrigation improvement program administered by the SCS in the Wellton-Mohawk Irrigation and Drainage District (WMIDD) in southwestern Arizona. The system was installed in May 1977, and has been in service since that time. Twenty-three lift-gate turnouts and two lift-gate checks were automated, using pneumatically-operated cylinders.

PROCEDURE:

Improve and develop gates, actuators, signaling devices, control center components, and power sources considering cost, simplicity, and reliability. Procedures will involve construction or adoption of new or improved devices followed by adequate field evaluation. Investigate extending single field automation to automatic control of all irrigation on a farm unit and finally, implementation of automatic controls on an irrigation district-wide basis. Assist the Soil Conservation Service, private consultants, and equipment distributors in design and installation procedures for automated systems. Encourage commercial development of automated equipment components.

RESULTS AND DISCUSSION:

Six automated irrigation systems have been installed in the Wellton-Mohawk Irrigation and Drainage District through 1980, Table 1. Included are 68 basins, totaling 465 acres. The original two were at our request to the cooperating farmers and were primarily for research and demonstrational purposes. The last four are operational systems for which we have provided design, installation, and maintenance assistance but they have been operated by the owner/operator. These latter farm sites, although operational, have been used for further research, development, and evaluation.

Six additional automated systems have been designed through 1980, Table 2. This includes 169 basins on 896 acres. Basins range from 10 acres on clay loam soils to just over 3 acres on sand. No specific plans have been made for completion of these systems.

Woodhouse Automation -- Lift-Gates

This system, installed in 1975, was used through early 1980. The cooperators discontinued use in the spring of 1980 because incoming flows from the Irrigation District were fluctuating during the 18-20 hour irrigation period which caused significant under- and over-water applications when the time based controller was used. The system had functioned satisfactorily during the first 5 years, and all components worked when checked in April 1980. Volumetric control will be added to the system during 1981. The cooperators have agreed to continue use of the system once the conversion has been made.

Naquin Automation -- Ports

The automated port system was used some during 1980 but use was interrupted by polyethylene and copper tubing failures at different times during the year. Copper tubing corroded in two locations where it came out of the ground. Corrosion was likely caused by an accumulation of salts at the soil-air interface. Sections were replaced and coated with an asphaltic material.

The polyethylene tubing used to signal checkgate 2 leaked when used during an irrigation in May, hence the checkgate would not function. The air tube returning to the control center from the overflow at checkgate 2 was used to replace the open tube. Operation was continued until August when checkgates 1 and 2 and basin gate 8 would not function. We were able to trace the tubing to field gate 8 and found both the signal and supply tubes to be chewed by gophers. The tubes had not been protected. We were unable to find the cause for the checkgate malfunctions, but likely was also caused by rodents. Use of the system was necessarily discontinued. We have agreed to replumb the air supply to the ports and to upgrade the system by using electrical signaling and volumetric control. The cooperator is willing to continue usage of the upgraded system to provide longevity tests for components associated mainly with gate actuation (ports and lift-gates).

McDonnell-McElhaney #1

1980 completed 4 years' operation of this automated system. The system has been used for about 100 irrigations, and continues to work satisfactorily. The canvas sleeves placed on the cylinder rods in January 1979 continue to provide the needed protection against a rust-type buildup experienced during the first 2 years the system was used. Plans are being made to install volumetric control equipment at this site during 1981. Associated equipment will include a digital controller, matrix selection panel, and electrical/pneumatic conversion using solenoid-operated air valves.

Hoffman Automation

The two Hoffman automated systems were used on a limited basis during 1980. The systems featured several concepts that had not been tried previously: (a) air cylinder mounting reversed from that used on earlier systems; (b) electrical wire and tubing embedded in the concrete lined canal, and (c) portable control center independent of 110 VAC power.

Several problems developed with these systems over the 2-year period. The problems and changes made and planned are outlined:

a. Air leakage was significant around the rod end of the air cylinders. Cylinders were originally mounted with the rods up for protection against weathering between irrigations -- rods retracted inside cylinder. Dust accumulation around the rods also caused more leakage. When pressurized, the rod end of a cylinder will inherently leak more than the non-rod end. For these reasons, to reduce air usage of the systems, the cylinders were reversed in 1980 (rod end extended when gate closed) and canvas sleeves were added to protect the rods. Several air consumption tests were conducted. Air consumption with the rods upright and all gates closed (no cycling) averaged 3 and 4 ft^3/hr and ranged between 2 and 8 ft^3/hr. When the cylinders were reversed the consumption was about one-third the original (1.0-1.5 ft^3/hr). Both usages would be tolerable with the bottled air supply (60-75 and 160-230 hrs/bottle) but when the cylinders were cycled the usage was unpredictable. If all air cylinder rod seals were functioning properly, losses would not be much higher than reported. But in most instances, at least one cylinder would leak appreciably during an irrigation requiring excessive air and in some instances would empty a bottle or cause the DC powered air compressor to operate excessively. Air usage, however, is tolerable when considering an AC powered air compressor.

b. The embedded wire and tubing at Hoffman Enterprises #1 remained functional through 1980. The new wire and tubing encased in PVC in 1979 at the Joe Hoffman #1 system also functioned properly during 1980.

c. The portable control center, although functional, created several limitations in proper usage of the automated systems. Since air usage was unpredictable, the fixed volume air bottle approach to supplying air for the systems was unsatisfactory. The inconvenience of exchanging the bottles on a regular basis was also a concern. Maintenance of batteries was somewhat of a problem.

Considering the various problems outlined, plans are being made to provide AC power to each site and to add volumetric control equipment and associated controller. Hoffman plans to move an AC powered air compressor from site to site for each irrigation. Volumetric interface equipment and the controller will be permanently fixed at each of the field sites.

McElhaney-McDonnell #2

At the request of the Soil Conservation Service and McElhaney and McDonnell another automated system was designed and installed in 1980. The 76-acre field is divided into nine basins with water applied from a concrete-lined canal about 2300-ft. long, Figure 1. Single lift-gate inlets to the individual basins were automated. The system is on relatively steep terrain which required four checkgates. Checkgate and safety overflow locations are shown in Figure 1.

This system features the first volumetric control equipment used on any of the systems in the WMIDD. In addition new procedures for signaling field gates were tried; control center logic was developed to meet the requirements of safety overflow; checkgate signaling; and water disposal after shut-down; and procedures for equipment installation were simplified.

The basic components to attain volumetric control rather than time based control were:

a. 12-station microprocessor based controller/timers manufactured by RainBird Sprinkler Mfg. Corp. (Model CIC-12)1/ -- available commercially.

b. Capacitance probe used to detect water level (depth) at flume and associated electronic package required to attain depth to electrical signal and linearizing equipment. Equipment used was produced by Endress and Hauser, Inc.1/ and included:

1. Capacitance probe and level measurement package. An electromagnetic field is set up between the probe and wall of the vessel. As the capacitance changes (as water rises between the probe and wall), this change is translated to a linear DC output which is water level proportional.

2. Electronic flow converter. Converts the non-linear output signal provided by the equipment described in (1) to an output proportional to flow of a non-linear primary flow measuring device such as a flume. This output, proportional to flow, can be volts, amps, or pulsed output. For this particular system the pulse generator system was used.

c. A pulse generator. Time-based controller interface was developed in cooperation with the RainBird Sprinkler Mfg. Corp. to adjust the time base as flow rate changed from a pre-selected nominal flow rate. Features of the interface system included:

1. Select resolution of either 1- or 6-minute (1/10 hour).

2. Default to time base, at pre-selected nominal flow, if pulse signal lost or if not received in pre-established time frame.

3. Nominal flow arbitrary and at operator's preference.

An irrigation guide for McElhaney-McDonnell #2 (MM #2) was developed in which controller settings are illustrated for each basin for various application depths, Figure 1. These settings represent time at nominal flow (minutes for application depths less than 3-1/2 inches and hours otherwise). Nominal flow was selected as 24.4 ft^3/s, hence one minute at nominal flow represents 0.407 acre-inch (1464 ft^3). The interface reduces nominal time units if the flow rate is greater than nominal and increases the time units for flows below nominal, effectively adjusting volume delivered by the changed time periods.

The temperature stability of the capacitance probe was evaluated extensively at the laboratory, both indoors and outdoors. In addition the probe-interface-controller system was evaluated and found to work

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1/ Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by USDA.

satisfactorily. The volumetric equipment was installed in October 1980 and was used four times through the end of 1980. The effectiveness of the volumetric equipment is shown in Table 3, in which the adjustment of the time based controller is illustrated for a flow rate of about 1 ft^3/s below nominal (23.4 ft^3/s or 4.1%). The adjustments are satisfactory, especially since the resolution is limited to one full digit (1 minute).

The functional requirements of safety overflow, checkgate signaling, and water rundown after the final basin was irrigated were developed, Table 4. The logic center was then designed and built to provide the necessary functions, first using a microprocessor based system, and later using electro-mechanical relays. The relays are favored over the microprocessor since they are more readily maintained if a malfunction should occur. The relay logic center was installed in early 1981.

The system is remotely started by operation of the first overflow near basin gate 2, Figure 1. The controller requires a switch closure to remotely start. Since checkgates are normally open, the first checkgate must be closed to effect an overflow (go to station 1 of controller when field canal nearly full). Two DPDT relays were used to provide the remote start, Figure 2.

The controller used, advances through the 12 stations in sequence. To provide random sequencing a matrix board was used, Figure 3, with input to the board from the controller (nine stations for MM #2) and output to the basin stations — input to the control center logic relays. In addition, the gates can be operated manually (if controller should malfunction) by pinning the desired basin on the MANUAL row of the matrix. Gates to be used in case of overflow and excess water disposal can be selected at the matrix. The MANUAL matrix row is continually powered by 24 VAC, input to O.F. #1 and O.F. #2 is from the float switches at overflows 1 and 2, respectively, and RUNDOWN input is from station 10 of the controller.

Rather than hardwiring from the control center to each gate, a pair of 14 ga wires were daisychained to all gates to power the 24 VDC solonoid operated 4-way air valves. Switching the 24 VDC power to specific gates (valves) was accomplished by using a 24 VAC SPDT relay, signaled using 22 ga telephone wire, Figure 4. A 24 VDC power supply was selected with adjustable voltage output and remote sensing features. The output voltage is adjusted to provide the required nominal 24 VDC near the load center. For the MM #2 field a pair of 22 ga wires are used to sense the voltage near basin 6.

General

Gate modification to receive the air cylinders has been standardized by attaching the cylinder to an angle-iron welded to the gate, and a connector between the cylinder rod and rod used to manually open the gate. Generally, an 18 inch gate opening is adequate. Normally open gates (with helical springs) use a 4-1/2-inch bore cylinder while normally closed gates (no spring) use a 3-1/2-inch bore cylinder. Closure force of a normally open gate at 60 psi is 950 pounds while opening force of a normally closed gate is 530 pounds. Helical springs used on the MM #2 system were the same as those on the Hoffman automation. They were mounted externally rather than internally as has been done in the past. The springs provide a gate opening of 13 to 14 inches with a spring force of about 500 pounds when displaced (compressed) 18 inches.

A parts list has been developed for the automated lift-gate systems to accommodate the SCS and farmer requests. The list is divided into sections: control center, gate modification, overflow, and miscellaneous materials from control center to gates.

SUMMARY AND CONCLUSIONS:

Six fields of level-basins have been automated through 1980 in the Wellton-Mohawk Irrigation and Drainage District. The original two (Woodhouse and Naquin) were at our request, and were for research and demonstration purposes. The last four (McElhaney-McDonnell and Hoffman — two systems each) are operational systems for which we have provided design information and installation assistance. Even though the latter four systems are operational they have been used for research, development, and evaluation purposes. Items such as (1) control center independent of 110 VAC power; (2) bottled air or nitrogen gas used to power gates; (3) encasement of electrical wire and air tubing for gopher protection in concrete, during lining of the canal and two techniques of placement in PVC pipe; (4) air cylinder placement/rod protection; (5) different procedures for signaling gates; (6) modified control center logic using microprocessor and electro-mechanical relays to provide the requirements of safety overflow, checkgate signaling, and water disposal after shutdown; (7) simplified procedures for equipment installation; and (8) development of an equipment package (from commercial sources) to provide volumetric rather than time based control; have all been research/development items over the past 4-year period.

To date 465 acres have been automated in the Wellton-Mohawk Irrigation and Drainage District which includes 68 basins and 13 check gates. We have provided design information for an additional 896 acres, but no specific plans for completion have been made.

Gophers chewed some polyethylene tubes on the Naquin automated port system in 1980. Hence after 5 years' operation the unprotected tubes failed. The system well be replumbed and rewired during 1981.

The air cylinders used on the two Hoffman systems were mounted with the rod end up — reverse of all previous systems. When pressurized, the rod end of a cylinder inherently leaks more than the non-rod end. Dust and debris also collect on the ends of the cylinders between irrigations, and are pulled into the rod seal when operated. Resultant leakage may be excessive and is unpredictable. The cylinders were reversed in 1980 with the rod end down. I am recommending such a cylinder gate mounting on all future systems.

One system, in which the electrical wire and polyethylene tubes were encased in the concrete when the canal was slipformed, remained functional during 1980.

Maintenance of batteries (rechargeable) and air bottles (replacement) created some limitations in proper useage of the Hoffman automated systems which were independent of 110 VAC power. Provisions are being made to provide AC power to each site to reduce the maintenance requirement of the portable control center.

A new automated lift-gate system was designed and installed on the McElhaney-McDonnell farm during 1980. The 76-acre field is divided into nine basins which range from 3.3 to 8.7 acres. The system featured (a) an equipment package to provide volumetric rather than time based control of the switching decision from basin to basin and (b) new procedures for signaling field gates. Control center logic was developed to meet requirements of safety overflow, checkgate signaling, and water disposal after shutdown. A capacitance probe was used to detect the water depth at the flume. The performance requirements for the volumetric equipment was provided to commercial firms. Subsequently, interface equipment between a commercially available controller and the capacitance equipment was developed by the controller manufacturer. The entire package (controller, interface, and capacitance probe) was thoroughly tested under controlled laboratory simulations of field conditions and was subsequently installed in the field. It was used to control four irrigations through the end of 1980.

All automated sites in the Wellton-Mohawk Irrigation and Drainage District will be fitted with volumetric control equipment during 1981.

<u>PERSONNEL:</u> Allen R. Dedrick

Table 1. Automated irrigation systems in Wellton-Mohawk Irrigation and Drainage District

Year Installed	Owner/Operator	Acres	Number of Basins	Number of Checkgates	Number of Overflows
1975 1/	Woodhouse	65	8	1	2
	Naquin 2/	70	8	3	3
1977 3/	McElhaney & McDonnell #1	64	23	2	4
1979 3/	Joe Hoffman #1	110	8	2	3
	Hoffman Enterprises #1	80	12	1	2
1980 3/	McElhaney & McDonnell #2	76	9	4	5
	Total	465	68	13	19

1/ Research/Demonstration at USDA-SEA-AR request.

2/ Automated ports — all others were lift-gates.

3/ Operational systems, cost shared by SCS.

Table 2. Automated irrigation systems designed at the request of individual owner/operators or the Special Projects Office of the SCS in Wellton, Arizona. All systems are in the Wellton-Mohawk Irrigation and Drainage District

Owner/Operator	Acres	Number of Basins	Number of Checkgates	Number of Overflows
Naquin (Davidson)	100	11	3	4
Naquin (Lower 80)	80	8	2	3
Hoffman Enterprises #3	187	20	10	9
Hoffman Enterprises #4	104	14	5	6
Gillette	55	18	4	6
Roth & Kemp	370	98	14	15
Total	896	169	38	43

Table 3. Effectiveness of volumetric equipment in adjusting time based controller to reflect a flow rate somewhat below the 24.4 ft^3/s nominal flow rate. Data obtained during an irrigation at McElhaney-McDonnell #2 in January 1981 on the first six basins.

			Irrigation Time		
Basin	Area	Flow Rate[1/]	Set	Calculated[2/]	Actual Measured
	(Acres)	(ft^3/s)	(Minutes)		
1	3.3	23.5	19	19.7	20
2	8.0	23.1	45	47.5	47
3	4.9	23.4	28	29.2	29
4	8.1	23.4	46	48.0	47
5	8.7	23.4	54	56.3	56
6	8.4	23.7	59	60.7	62

1/ Values determined from electronics.

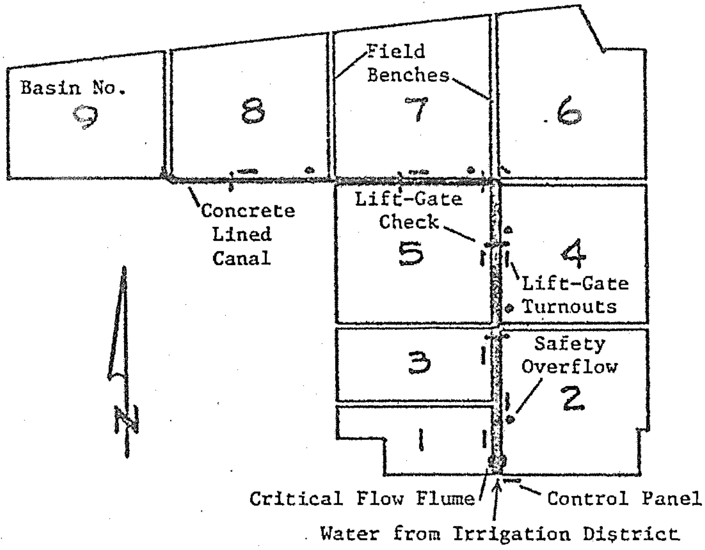
2/ Calculated using ratio of nominal flow rate to actual flow rate measured.

Table 4. Functional requirements of automated gates on McElhaney-McDonnel #2. A logic center was designed and built to meet these functional requirements using electro-mechanical relays.

Gate Number 1/	Conditions for Gate to Operate
Basin 1	Signal from controller to basin 1 or overflow 2 sensed and basin 1 selected as overflow basin (refer to Figure 3).
Basin 2	Signal from controller to basin 2 or overflow 1 sensed and basin 2 selected as overflow basin.
Basin 3	Signal from controller to basin 3 or overflow 1 sensed and basin 3 selected as overflow basin.
Basin 4	Signal from controller to basin 4 or overflow 2 sensed and basin 4 selected as overflow basin.
Basin 5	Signal from controller to basin 5 or overflow 2 sensed and basin 5 selected as overflow basin.
Basin 6	Signal from controller to basin 6 or overflow 3 sensed.
Basin 7	Signal from controller to basin 7 or overflow 4 sensed or when in rundown mode basin 7 selected as rundown basin.
Basin 8	Signal from controller to basin 8 or overflow 5 sensed or when in rundown mode basin 8 selected as rundown basin.
Basin 9	Signal from controller to basin 8 or when in rundown mode basin 8 selected as rundown basin and basin 9 not selected as rundown basin and overflow 5 not sensed.
Checkgate 1	Signal from controller to basins 1, 2, or 3 and overflow 1 sensed but checkgate 1 not selected as overflow gate and not in rundown mode.
Checkgate 2	Signal from controller to basins 4 or 5 and overflow 2 sensed but checkgate 2 not selected as overflow gate and not in rundown mode.
Checkgate 3	Signal from controller to basin 6 and overflow 3 not sensed and not in rundown mode.
Checkgate 4	Signal from controller to basin 7 and overflow 4 not sensed and when in rundown mode basin 7 selected as rundown basin and basins 8 and 9 not selected as rundown basins.

1/ Basin gates 1 through 8 normally closed while basin gate 9 and all checkgates normally open.

IRRIGATION GUIDE



BASIN	ACRES	CONTROLLER SETTING, MIN. APPLICATION DEPTHS, IN.				
		1-1/2	2	2-1/2	3	3-1/2
1	3.3	14	19	23	28	32
2	8.0	34	45	56	68	79
3	4.9	21	28	34	41	48
4	8.1	34	46	57	68	80
5	8.7	37	49	61	73	86
6	8.4	35	47	59	71	83
7	9.2	39	52	65	78	91
8	8.5	36	48	60	72	84
9	7.5	32	42	53	63	74

BASIN	ACRES	CONTROLLER SETTING, HR. APPLICATION DEPTHS, IN.								
		4	4-1/2	5	5-1/2	6	7	8	9	10
1	3.3	.6	.7	.8	.9	.9	1.1	1.2	1.4	1.5
2	8.0	1.5	1.7	1.9	2.1	2.3	2.6	3.0	3.4	3.8
3	4.9	.9	1.0	1.1	1.3	1.4	1.6	1.8	2.1	2.3
4	8.1	1.5	1.7	1.9	2.1	2.3	2.7	3.0	3.4	3.8
5	8.7	1.6	1.8	2.0	2.2	2.4	2.9	3.3	3.7	4.1
6	8.4	1.6	1.8	2.0	2.2	2.4	2.8	3.2	3.5	3.9
7	9.2	1.7	1.9	2.1	2.4	2.6	3.0	3.5	3.9	4.3
8	8.5	1.6	1.8	2.0	2.2	2.4	2.8	3.2	3.6	4.0
9	7.5	1.4	1.6	1.7	1.9	2.1	2.5	2.8	3.2	3.5

Figure 1. Field layout for automated irrigation system on McElhaney-McDonnell (MM #2) farm (9 basins, 76 acres, and concrete lined canal about 2300 ft long) and controller settings for 24.4 ft^3/s flow rate.

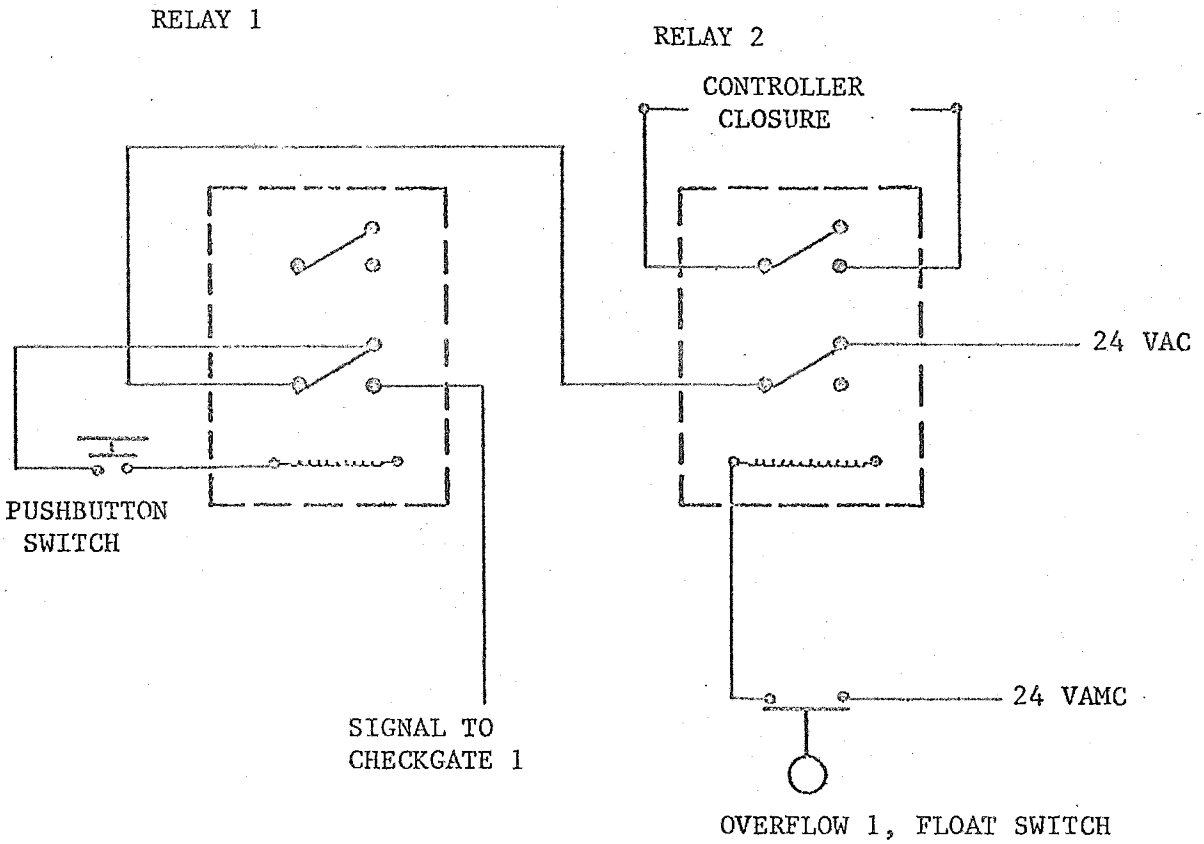


Figure 2. Schematic diagram of two DPDT relays used to effect automatic (remote) start of the controller when an overflow is sensed. System shown before set for autostart. To set the system for remote start the operator momentarily closes the pushbutton switch, which latches relay 1 and provides a 24 VAC signal to checkgate 1 (closes gate) -- autostart armed. When an overflow is sensed, the float switch closes, causing relay 2 to switch which provides a circuit closure to the controller (advances to first station) and opens the 24 VAC power supply which disarms relay 1. Any subsequent overflow closure will cause relay 2 to switch but will not adversely affect the controller.

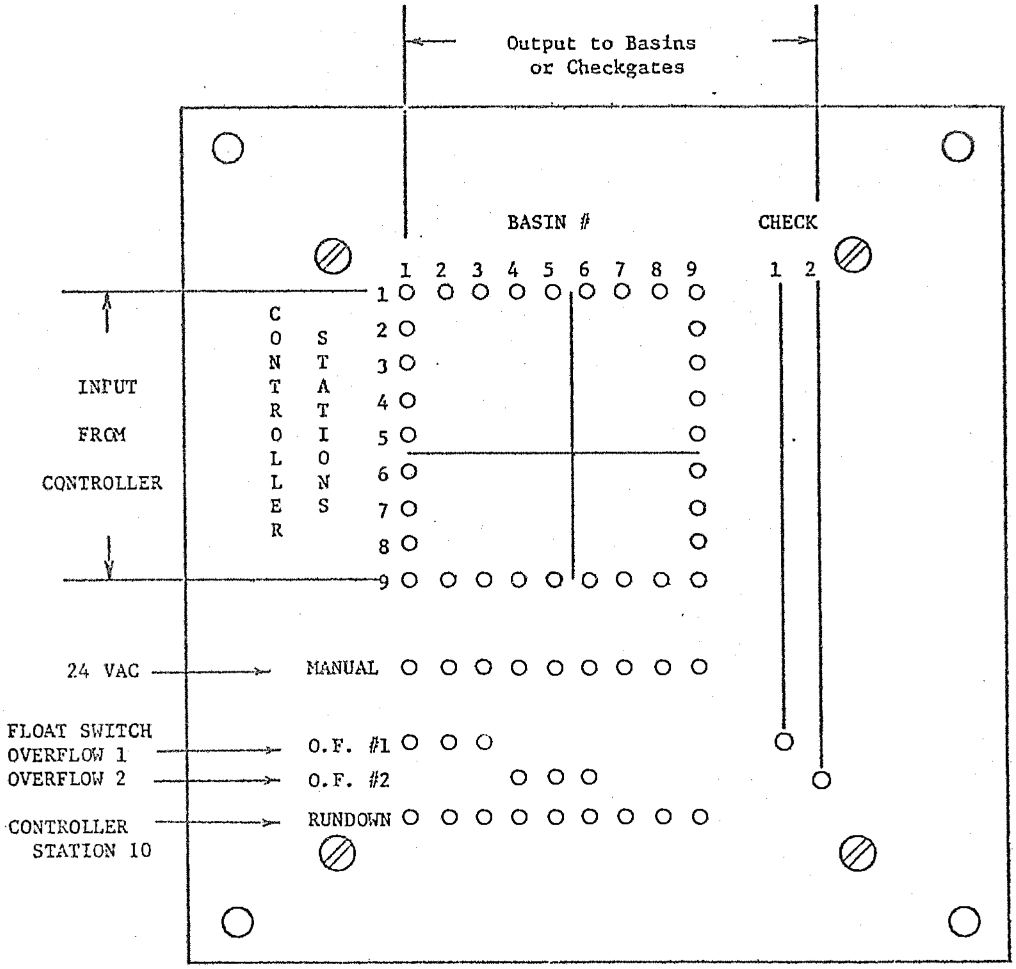


Figure 3. Matrix board located at the McElhaney-McDonnell #2 Control Center, to provide random sequence selection, manual rather than controller operation, gate selection if overflow sensed at first two overflows of system, and excess water disposal after last basin irrigated (RUNDOWN).

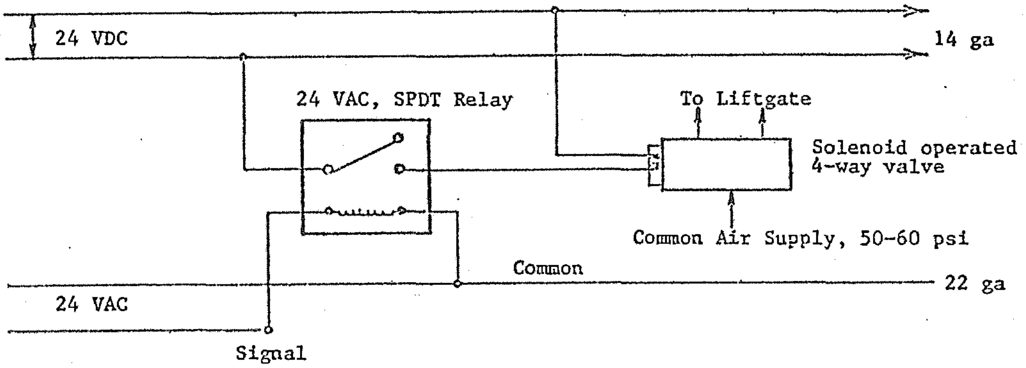


Figure 4. Diagram of relay and solenoid operated air valves located at each gate of the McElhaney-McDonnell #2 automated irrigation system.

TITLE: RUBBER AND RESIN ANALYSIS IN GUAYULE

NRP: 20740 CRIS WORK UNIT: 5510-20740-TBD

INTRODUCTION:

Reliable rubber and resin analyses are required to insure proper evaluation of rubber and by-product production by the guayule plant. Various solvent extraction methods have been developed with some depending upon lengthy extraction procedures (Spence and Caldwell, 1933); and the need for careful sample preparation (Holmes and Robbins, 1974). Garrot et al. (1981) adapted liquid nitrogen freezing of the plant material to avoid extensive grinding and to speed sample preparation. Other methods are available such as the turbimetric (Traub, 1946) and the nuclear magnetic resonance techniques (Yokoyama, 1980). The equipment cost of the latter system is prohibitive for most analytical laboratories. No "standard" analytical procedure has been adapted for universal use at present.

Rubber analyses for a large number of samples were anticipated with the work being initiated on guayule production at this laboratory. Since no reliable source could be used to analyze our sample, investigations were started to develop one that fitted our immediate needs.

PROCEDURE:

Plant samples were dried in a convection oven at 50°C for 24 hours to 7 days. The larger samples were cut into small pieces to hasten drying. Dried samples were ground in a Wiley mill and passed through either 10 (2 mm)- or 20 (1 mm)-mesh screens. The ground sample (100 to 250 mg) was treated with 10 ml acetone in a 50-ml culture tube. The stoppered tube (aluminum foil protected the neoprene stoppers) was placed in an ultrasonic bath system for 15 minutes to cause continuous, rapid agitation of the plant sample in the solvent. The mixture was centrifuged at 2000 rpm for 8 minutes, and the supernatant liquid decanted into pre-weighed aluminum weighing dishes. Acetone extraction was repeated twice for a total of three extractions. (A separate study showed that this was sufficient to extract out the acetone-soluble resin.) The liquid-resin mixture was dried to constant weight in a fume hood at room temperature and resin estimated from the final weight.

The acetone-treated residue in the tube was dried at 50°C. Then, 10 ml of one of the rubber extractants, hexane, cyclohexane or tetrahydrofuran (THF) were added to the acetone-free residue. The remaining rubber extraction procedure followed that for the acetone extraction. The percent of rubber and resin was based on 50°C dried plant materials.

RESULTS AND DISCUSSION:

The percentages of resin and rubber extracted from a 200 mg sample size with the various solvents are compared in Table 1. The THF extracted approximately two times the rubber than the other solvents. The hexane and cyclohexane, however, gave values closer to the NMR analysis. Reproducible resin analyses (coefficient of variation of 3%) could be obtained with the acetone extraction. The rubber extraction was more variable (11 to 16% coefficient of variation). This variability could be decreased by using a larger sample size.

Table 1. Resin and Rubber Extracted from a Guayule Sample

Resin (Acetone)	Rubber
5.4 ± 0.1	1.3 ± 0.3 (Hexane)
5.3 ± 0.2	1.6 ± 0.2 (Cyclohexane)
5.4 ± 0.2	2.7 ± 0.4 (Tetrahydrofuran)
---	1.7 (NMR)[a/]

a/ Nuclear magnetic resonance analysis by H. Yokoyama, Fruit & Vegetable Chemistry Laboratory, USDA-AR-SEA, Pasadena, California.

The solvent extraction technique used here removes rubber plus any other materials soluble in the solvent. Similar procedure made on cotton stem samples with the three solvents gave values of 0.4% extractable material. However, the possibility exists for relating rubber extraction percent by the solvent method with the NMR technique so that a regression equation can be developed between the two analytical methods. As indicated earlier, the extraction method requires less expensive equipment. In the procedure used here 25 to 50 analyses could be run per day, once the plant samples are ground.

SUMMARY:

The solvent extraction technique was tested using three different solvents for determining rubber in the guayule plant. The method is rapid and requires only standard laboratory equipment. The initial results give analytical values close to another independent method. Additional work needs to be done, however, to improve on the precision and to cover the wider range of rubber content that will be encountered in the field.

REFERENCES:

Garrot, D. J., Jr., Johnson, D. L., Rubis, D. D., and Dill, G. M. 1981. Extraction of rubber from guayule using liquid nitrogen. Anal. Chem. 53:543-544.

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Traub, H. P. 1946. Rapid photometric methods for determining rubber and resins in guayule tissue and rubber in crude-rubber products. USDA Tech. Bull. 920.

Yokoyama, H. 1981. Personal communications.

PERSONNEL: F. S. Nakayama, B. A. Rasnick

TITLE: MOISTURE STRESS AND WATER-USE RELATIONS OF YOUNG GUAYULE PLANT

NRP: 20740 CRIS WORK UNIT: 5510-20740-TBD

INTRODUCTION:

An important requirement for the successful commercialization of guayule for rubber production is an adequate understanding of the water requirements of the plant. While guayule is considered drought tolerant in its native habitat, improvement in rubber yields can be achieved by promoting faster biomass production and higher rubber content through controlled supplemental irrigation. The quantity of water applied and irrigation timing are important factors to be considered since rubber synthesis and/or accumulation is related to environmental stress imposed on the plant.

Methods are under development for scheduling irrigations based on plant water stress measurements using infrared thermometric techniques (Idso et al., 1981; Jackson et al., 1981). Because of guayule's different growth pattern and product compared to the economic crops used in previous investigations, studies were undertaken to determine whether remote sensing techniques could be used to characterize water stress in the drought adapted guayule, and how it can be used for scheduling irrigation.

PROCEDURE:

The guayule experiment originally designed for subsurface CO_2 enrichment studies was modified to accommodate the moisture stress investigation.

Two varieties (593 and 11591) of 3-month-old guayule seedlings originally grown in the greenhouse were transplanted on 23 April 1980, on 3.0 by 1.8 meter plots. Four plant rows 46 cm apart with plant spacing of 36 cm were used per plot. Three water content levels in the soil profile were selected. Irrigation was made when 65, 80 and 95% of the available water to a depth of 160 cm was removed. Actually, differential moisture treatments were not begun until the third month when the transplants were well established. A 95% stand establishment was obtained. Irrigation was started first with subsurface line-source trickle tubing buried 15 to 20 cm deep. Tube damage by gophers, approximately 3 months after the beginning of the experiment forced a change to surface trickle lines.

Aluminum access tubes to a depth of 180 cm were installed in 12 of the randomly arranged treatment plots. Moisture readings were taken two to three times a week in the spring through fall and decreased to once a week during the winter months.

Plant temperature measurements with the infrared thermometer were started in September when the plants were approximately 20 cm tall. The plants were sufficiently large that the 3° angle of view of the infrared thermometer covered the entire plant and soil interference was not a problem. Four plants were used per plot, with two sets of measurements per plant, one taken from the west and the other from the east side of the north-south oriented plant rows. Readings were made on clear days between 1130 to 1330. Wet and dry bulb temperatures for determining vapor pressure deficit were taken with each set of plant temperature measurement. Infrared thermometer calibration was checked with a blackbody reference source before and after each run. Crop water stress indices were computed using both the Idso et al. (1981) and Jackson et al. (1981) techniques.

RESULTS AND DISCUSSION:

The relation between vapor pressure deficit and differences between plant and air temperatures (Figure 1) were similar in form to that described by Idso et al. (1980). The two guayule varieties had different relations, the slope were the same 0.17, but the intercepts were different; 1.20 and 0.46 for the 593 and 11591 varieties, respectively. The 11591 had leaf temperatures consistently lower by 0.5 to 1°C than the 593 variety. A reasonable explanation for this difference is not available at present.

The computed crop water stress indices (CWSI) based on Jackson et al. (1981) are related to the total soil water content in the 170 cm soil profile depth with time in Figure 2. The "dry" treatment with the 593 variety is used as an example. The CWSI values follow inversely the water content values. Rapid recovery from stress was shown after irrigation, and the stress then started to increase as moisture content decreased. The experiment was run in an abnormally warm fall with evapotranspiration being on the order of 5.0, 3.5, and 1.5 mm/day in September, October and November, respectively.

The day-to-day CWSI's can vary at times so that a few successive points cannot be used to pinpoint the stress status of the plant. Long term accumulation of CWSI such as the concept developed for the stress degree day indexing (Idso et al., 1977) appears to be applicable to define more closely the yield potential under water stress conditions.

SUMMARY:

Preliminary determination of the water stress index of the drought-adapted guayule plant shows that the guayule responds to soil moisture stress in a manner similar to the non-drought tolerant plants, such as wheat, alfalfa and cotton. Crop water stress indices are being developed for scheduling irrigation of these latter economic crops and such indices could be adopted for guayule water management also. The two varieties of guayule studied exhibited different plant temperatures under the similar environmental conditions and the cause for this should be investigated more thoroughly.

REFERENCES:

Idso, S. B., Jackson, R. D., and Reginato, R. J. Remote sensing of crop yields. Science 196:19-25. 1977.

See Appendix for additional references

PERSONNEL: F. S. Nakayama, D. A. Bucks

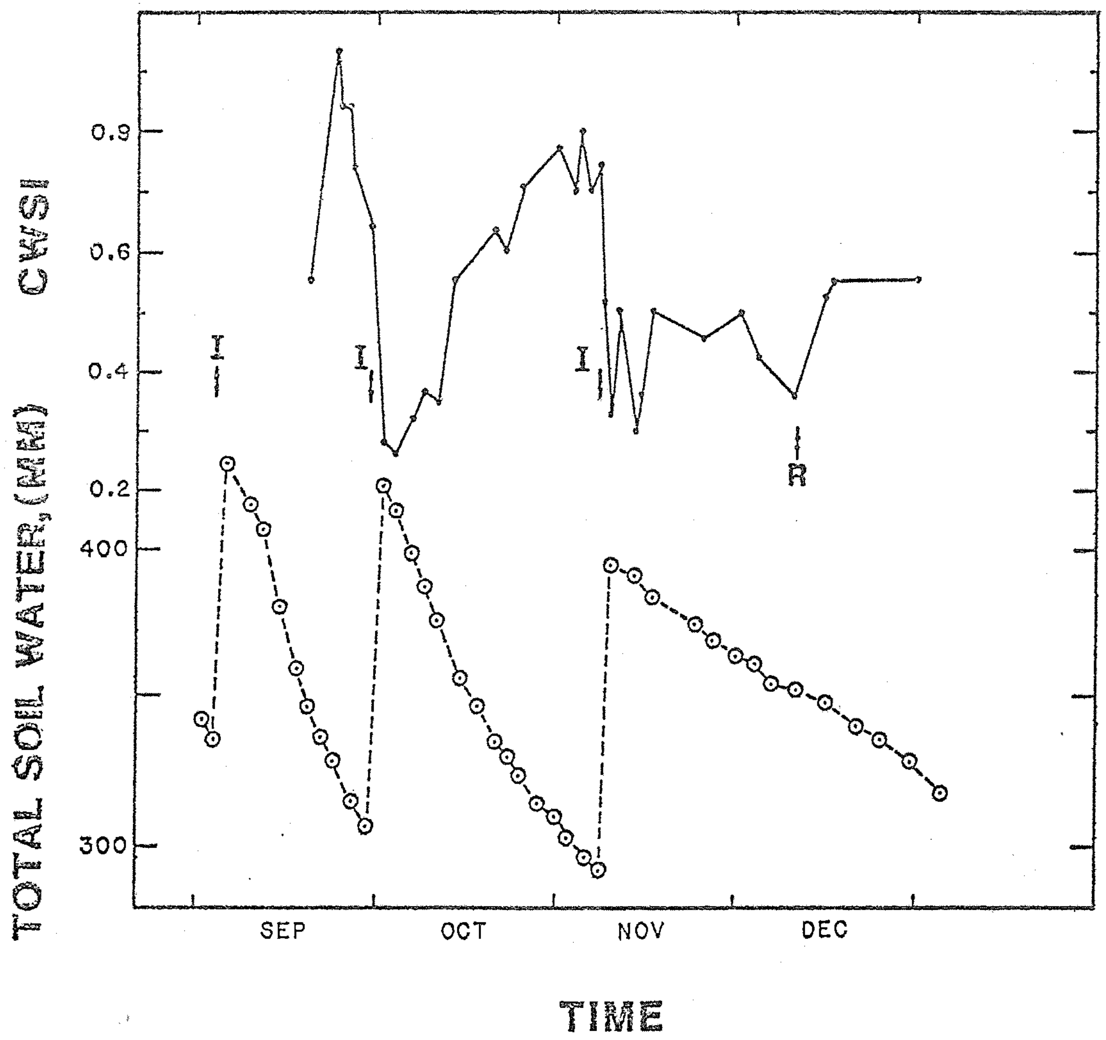

Figure 2. Crop water stress index (CWSI) and total soil water content changes as a function of time. "I" and "R" designate irrigation and rain, respectively.

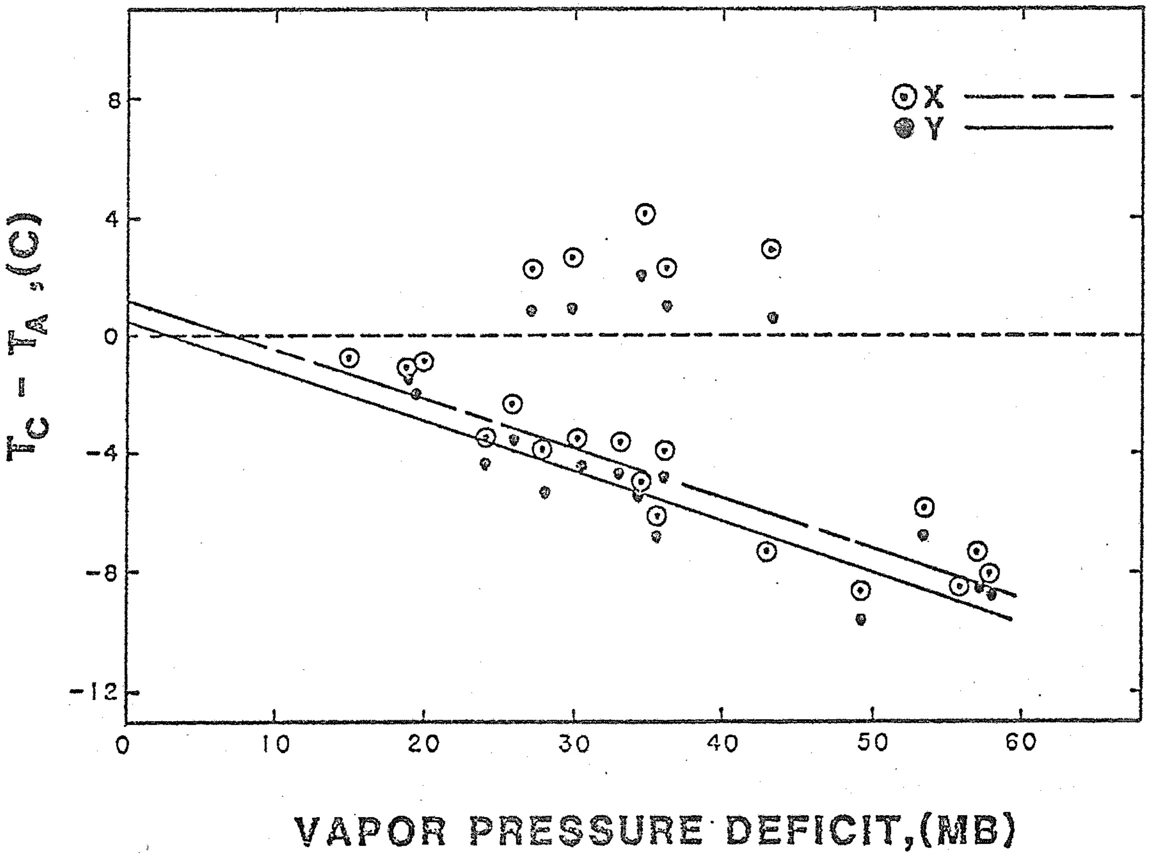

Figure 1. Relationship between vapor pressure deficit and crop temperature (T_C) and air temperature (T_A) differences. Symbol "X" and "Y" represent variety 593 and 11591, respectively.

Title: THE EVAPOTRANSPIRATION, YIELD, AND SOIL-PLANT-WATER RELATIONS OF GUAYULE

NRP: 20760 CRIS Work Unit: 5510-20760-002

INTRODUCTION:

Guayule is a small shrub native to the arid regions of northern Mexico and a small part of Texas. This shrub produces a high quality rubber, which has the potential of making the United States independent of foreign sources of natural rubber. Guayule is reported to be a low water user, but there is no sound information on total amounts of water to be applied or the optimum scheduling of irrigations as related to total rubber yield. In view of the strategic importance of this crop, there should be research to guide farmers in the irrigation management for maximum rubber yields. This laboratory's first study designed with these needs in mind is being undertaken at the University of Arizona's farm at Mesa, Arizona. Since there was no account of this research in last year's annual report, a portion of the abstract from a paper on the subject will be included here as background material. The paper, titled "Soil Water Depletion in Irrigated Guayule," by William L. Ehrler and Dale A. Bucks, was presented at the Third International Conference on Guayule at Pasadena, California, 27 April - 01 May 1980.

> "The objective of this experiment was to measure the water requirement and rubber yield under four levels of soil moisture. The first report deals with only the establishment period, when liberal irrigations were given to obtain good growth. There are two cultivars (593 and N565-II), each with 40 plants per treatment on raised beds irrigated with an underground trickle line in each bed, with an emitter every 20 cm by each plant. Plants are in double rows on beds centered 1 m apart. Neutron meter access tubes in three of the four replications provide data on soil water content at 20 cm increments from 20- through 160-cm depths. Peat pot seedlings transplanted on 29 May grew rapidly to a height and diameter of 30 cm by 13 August, when neutron meter measurements began.
>
> During this establishment period, water applications were: 102 mm from furrow irrigation at transplanting, 46 mm from rain, and 1184 mm from trickle lines. From 13 August to 13 November, rain was 28 mm and irrigation 615 mm. A uniform stand is present for both cultivars with no indication of early soil moisture stress. Cumulative soil moisture depletion from 13 August to 13 November was 666 mm for cv. N565-II, but only 422 mm for cv. 593. On 13 November, the drying cycle was started, leading to four different levels of soil moisture".

PROCEDURE:

The last irrigation of the first growing season was on 13 November 1979. Winter and spring rains sufficed to provide soil moisture until

8 April 1980, the first irrigation for the wet treatment. This treatment (No. 1), was a continuation of the one used previously, i.e., irrigation when 50 percent of the available water was depleted to a depth of 1 meter. Three drier treatments were studied, as given in Table 1.

Soil moisture was measured with a Campbell Pacific neutron meter in aluminum access tubes just before and three or more days after each irrigation in three of the four replicate plots for each of the four treatments, and for both cultivars, making a total of 24 sets of readings; at each access tube, 30-second counts were taken every 20 cm from 20- through 160 cm. A computer program was written to give volumetric water contents by depth and time, and appropriate averages and derived parameters were obtained, such as total amount of water in a given profile depth at a specific time.

A preliminary rubber analysis was made primarily to validate the method. Periodic sampling for rubber content will begin in June 1981.

RESULTS:

Soil Water Depletion. Fig. 1 is a plot of the amount of water (mm of water in 170 cm of soil) against time for the 1980 season, for guayule cv. N565-II, contrasting the two extreme treatments (No. 1, wet and No. 4, dry). Each data point is the mean of three replications. In the spring, there was sufficient rain to maintain the soil water content at a high level. Irrigation was begun in April 1980. Water applications were numerous enough to maintain the average soil water content at a considerably higher level in treatment No. 1 than in No. 4, thus meeting a primary objective.

It was found that a drying cycle had to be severe to cause a large decrease in soil water content. Therefore, the criterion for treatment No. 4 was no longer effective, i.e., a 95-percent depletion of soil water content in the upper meter of soil. Water stress greater than the conventional wilting point had to be imposed on treatment No. 4 to really reduce evapotranspiration substantially. Fig. 1 shows that there were five drying cycles severe enough to greatly lower water loss, but that evapotranspiration rapidly increased to high levels after irrigation.

Cultivar 593 was not able to lower the water content to quite as low a value as cv. N565-II (down to 160 mm of water in 170 cm of soil instead of about 145 mm). Otherwise, the data were quite similar in the two cultivars. This result is consistent with last years' data.

Calculations of the yearly evapotranspiration based upon the plot of Fig. 1 are being made now and will be presented in the next report.

Rubber and Resin Analyses. Resin and rubber analyses based upon acetone and tetrahydrofuran solvent extraction techniques (see the separate report on the analytical procedure) are presented in Table 2. The analyses were made on small branches taken from four separate plants per replicate. The plants were 18 months old from transplanting at the time of sampling. The rubber content of approximately 5 percent was not different among the different water level treatments or cultivars. The resin content of cv. N565-II was approximately twice that of cv. 593. Measurements of the two components will be continued on a 6-month interval.

SUMMARY AND CONCLUSIONS:

Doubling the amount of water applied to two guayule cultivars (by giving 25 as compared to 9 irrigations) resulted in no significant lowering of the rubber percentage for the 18-month-old plants. This is not consistent with earlier reports in the literature. The other item of consequence is the extreme drought tolerance of guayule. In designing this experiment, it was assumed that the dry treatment (No. 4) would be a rigorous test of drought tolerance. However, it was necessary to permit substantially lower levels of soil water content to develop (lower than 95 percent of the available water depletion in the upper meter of soil) before evapotranspiration was reduced materially. Considerably greater soil water stress over longer intervals on the dry treatment is necessary. A more stressful regime would help lower the total water application, which even for the 1980 dry treatment, amounted to 1110 mm, a total about the same as the evapotranspiration for a full-season cotton crop in the Salt River Valley.

PERSONNEL: W. L. Ehrler, D. A. Bucks, and F. S. Nakayama

Table 1. Treatment number, percentage available soil water depletion before irrigation, number of irrigations, and the total amount of water applied (exclusive of 208 mm of rainfall) to guayule cultivars 593 and N565-II in 1980.

Trt. No.	% Depletion	No. of Irrigations	Total Water Applied (mm)
1	50	25	2289
2	65	18	1824
3	80	16	1827
4	95	9	1110

Table 2. Rubber and resin content for young guayule plants (18 November 1980).

Treatment	Variety			
	593		N565-II	
	Resin	Rubber	Resin	Rubber
I	6.07±0.96	4.71±1.50	11.02±2.78	4.72±0.69
II	5.85±0.39	4.82±0.96	10.31±2.78	5.72±1.83
III	5.85±1.26	5.28±2.67	9.14±0.97	4.95±0.89
IV	5.69±0.72	5.08±1.04	9.89±3.00	4.80±1.78

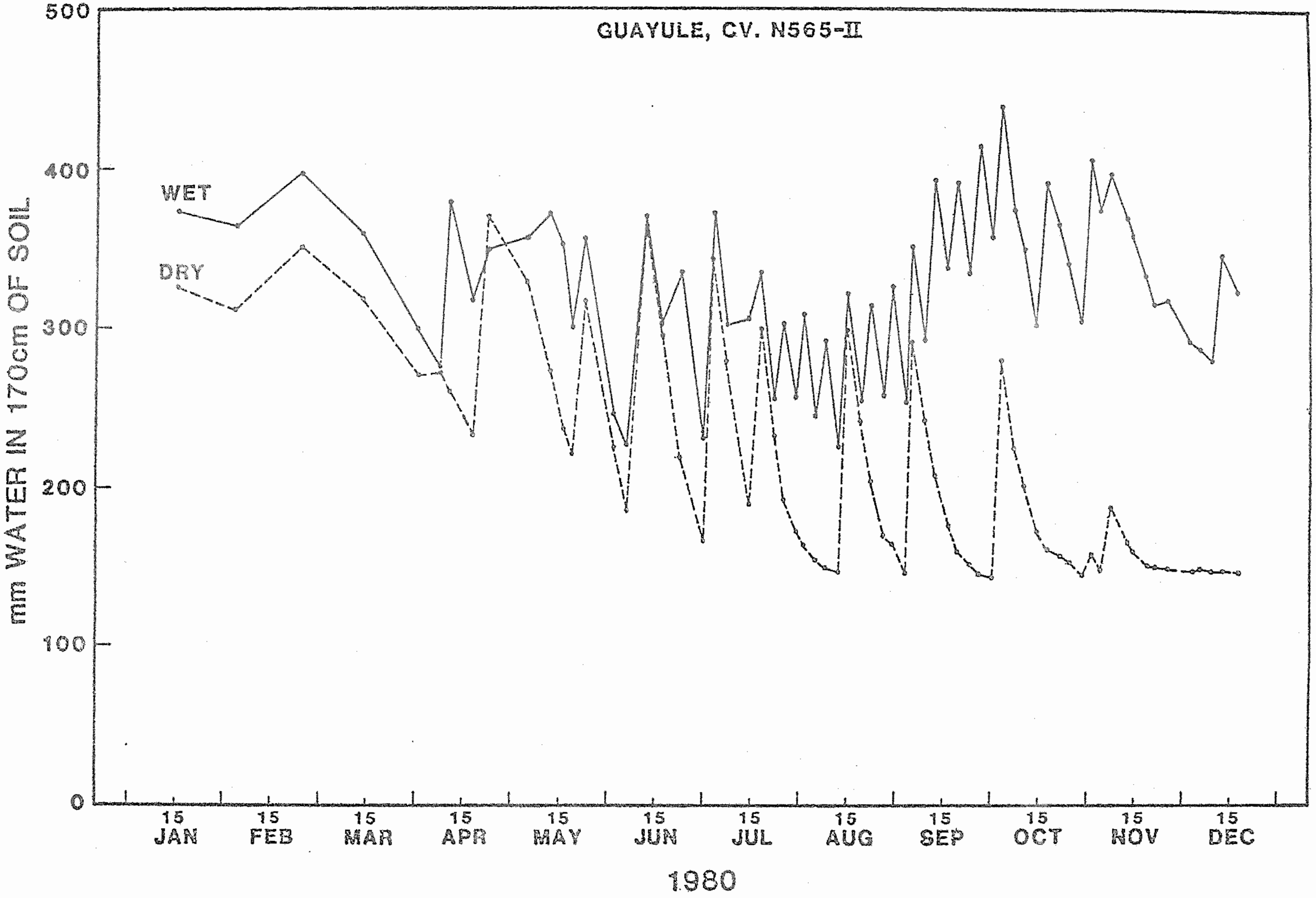

Figure 1. The amount of water in a 170 cm profile of soil under guayule cultivar No. N565-II, the mean value of three plots, for the wettest and driest of four irrigation treatments, throughout the 1980 growing season. The wet treatment received 25 irrigations, as compared to 9 for the dry treatment.

TITLE: RUNOFF-FARMING FOR DROUGHT-TOLERANT CROPS IN ARID ENVIRONMENTS

NRP: 20760 CRIS Work Unit: 5510-20760-002

INTRODUCTION:

Background information on our runoff-farming studies appears in the Annual Reports of 1973-1978. Six runoff-farming studies are in progress and a seventh one planned for 1981. The experiments are listed separately here, in the order of installation.

Jojoba: (Initiated in 1973). 1980 was the seventh year of the jojoba study at Usery Pass. Research effort was reduced in 1980 because three killing frosts within 6 years strongly indicated that runoff farming for jojoba may not be practical at that site. We concluded that augmentation of the summer rains through runoff farming resulted in lush late summer growth of the plant, which enhanced its vulnerability to late winter and early spring frosts. We believe that runoff farming for jojoba would be better adapted to a Mediterranean type of climate as in California or Mexico.

Horticultural Crops: (Initiated in 1978). 1980 was the third year of a study evaluating runoff farming for growing horticultural crops. The plot installation procedures and plot diagram showing the original 12 species appear in the 1978 Annual Report. Of the original 12 plants, two grape varieties, three almond varieties, a jujube plant, and the pomegranate still survive. Drought apparently killed the peach, apricot, olive, one grape variety, and a female pistachio tree planted in 1979. Frost killed the fig, but it has been replaced. New, surviving plants are a male pistachio tree and an asparagus bed.

Quetta Pines at Granite Reef: (Initiated in 1978). 1980 was the third year of the study for evaluating runoff-farming for growing Quetta Pine at our Granite Reef water-harvesting test site. Site preparation, runoff-farming treatments, tree planting and establishment procedures, and plot diagrams appear in the 1978 Annual Report. Evaluation of the experiment consisted of measurements of rainfall, runoff, soil water content (with neutron meter access tubes), tree height and trunk diameter, and leaf water potential (with a Scholander pressure device). Runoff was collected in a sunken tank at the lower end of a catchment (the tank being substituted for a plant) and measured by pumping out the water through a water meter. The trees have received only rainfall plus runoff water since 28 June 1978. The 293 mm of annual rainfall was magnified 2.3, 3.3, and 5.5 times by the control (bare, smoothed, untreated soil), clay-salt, and wax treated plots, respectively.

In spite of the extra water, the trees have done poorly; of the original 25 trees, five died during the dry fall of 1980 (one on the bare soil control, and two each on the other two soil treatments). Growth of most of the survivors is slow, not even approaching the reputed 1-m per year. Several, however, are growing quite well, (the tallest tree is 0.72 m), suggesting that through selection and breeding the tree could be adapted to this exceedingly harsh site.

Christmas Trees at Camp Verde: (Initiated in 1978). A Christmas tree runoff-farming experiment was installed in March 1979 at Camp Verde, Arizona. The climate there is milder than at Granite Reef: yearly rainfall averages about 300 mm (50 percent more than at Granite Reef), and average temperatures are lower. Rainfall patterns between these two sites, however, are similar; most of the rain occurs during the two periods December through February and mid-July into September. The rest of the year normally is extremely dry.

Two runoff-farming sites are located at Camp Verde: one on a silty loam soil (clay site) where the use of NaCl to enhance runoff is being tested, and the other a quarter mile away on a loamy sand (sand site) where residual-type wax for the catchment treatment is being evaluated.

Contoured level terraces are being used instead of individual microcatchments. Terraces were installed quickly and efficiently with a road-patrol grader. Catchment surfaces were further leveled and smoothed, and rocks removed with a tractor-drawn Harley landscaper from Glenmac, Inc. The landscaper simultaneously mixed in the 11,000 kg/ha salt on the clay catchments. These operations were completed shortly after the trees were planted. Compacting when wet completed the clay treatment.

The wax installation had to be delayed until the summer of 1980 because of weed problems. The sand catchments were compacted wet with a vibratory roller, stabilized with polyvinyl acetate emulsion (10 percent solution applied at 2 liters/m^2), and made water repellent with a slack wax (containing 2 percent Emory 6639 antistripping agent) sprayed on as a hot melt at 0.5 kg/m^2. Separate runoff monitoring catchments were installed at each site.

Three ratios of catchment-to-receiving basin widths are being evaluated at each site: 1:1, 2:1, and 3:1 at the sand site, and 2:1, 4:1, and 6:1 at the clay site. Width of the receiving basin portion was 1.5 m in all cases. Trees on both sites should receive comparable amounts of water because we anticipate nearly 100 and 50 percent runoff, respectively, from the wax and the salt treated catchments.

Two conifers are being evaluated: Quetta pine and Arizona cypress. The Arizona cypress is native to the area, growing wild on the slopes of the surrounding mountains, and is used extensively as a landscape tree in the Verde Valley where it thrives under irrigation. Two sets of terraces were built at each site to accommodate the two species. Each terrace is 37.5 m long and accommodates 25 trees spaced 1.5 m apart. Berms were installed between every fifth tree to trap water and to provide five replications of five trees for each treatment.

The 300 trees were transplanted in mid-March 1979, and were hand watered until the summer rains began in mid-August. Only the few replacements have been hand watered since then. Measurements taken were the same as those at Granite Reef.

Precipitation was well above normal the first year. More than 400 mm fell during the 10-1/2 month period from mid-August until 30 June 1980 (the closing date of this report). Neutron moisture meter data showed that all soil profiles were well watered by the end of the winter rainy season, regardless of catchment to basin ratio.

The Arizona cypress trees are growing extremely well. The average height of these trees 15 months after transplanting of 15-cm tall seedlings was 1 and 0.9 m on the sand and clay site, respectively (Fig. 1). Growth rapidly accelerated from April through June 1980. Furthermore, the cypress trees are quite uniform in size, the tallest being only about 25 cm taller than the average. These trees should easily grow 1 m a year; thus they should be harvestable for Christmas trees every 2 to 4 years using stump culture (cutting to the lowest live branch). They make an impressive stand within the surrounding desert.

As at Granite Reef, the Quettas have been slow to start, but they are beginning to grow more rapidly (Fig. 1). The tallest Quetta pine on 19 June was 80 cm. The Quettas also are more variable in their growth habit than the cypress. All trees were fertilized with ammonium phosphate in February 1980, and three of each five replications of the Quettas were inoculated in April with mycorrhizae from a local established stand. We hope that these pines will soon attain the rapid growth that others have observed for them. Additional details regarding the runoff farming studies will be published in the manuscript, "Evaluation of materials for inducing runoff and use of these materials in runoff farming (in press).

SUMMARY AND CONCLUSIONS:

Conducting runoff-farming experiments with several plant species and at widely varied geographical sites helps to formulate guidelines for success. First, one must use highly drought tolerant species, because arid lands rarely have a favorable rainfall pattern. Second, the soils should store adequate available water, by having a moderately fine texture and/or being deep. Precise limits are hard to define yet, but the soils at Granite Reef and Usery Pass probably are borderline for runoff farming, at least in such a hot climate (pan evaporation greater than 1800 mm/year and annual rainfall only about 200 mm). Field capacity at Usery Pass is only about 12 percent by volume, thereby limiting the amount of available water for a plant unless inordinately deep soil reservoirs exist to be exploited by roots.

At Camp Verde not only is evapotranspiration less, but the soils also have greater amounts of available water, thus permitting a plant to tolerate drought better. Although these comments do not necessarily rule out further research at sites like Usery Pass, they do lend support to the desirability of sites like those at Camp Verde for enhancing the likelihood of success in runoff farming endeavors.

PERSONNEL: W. L. Ehrler and D. H. Fink

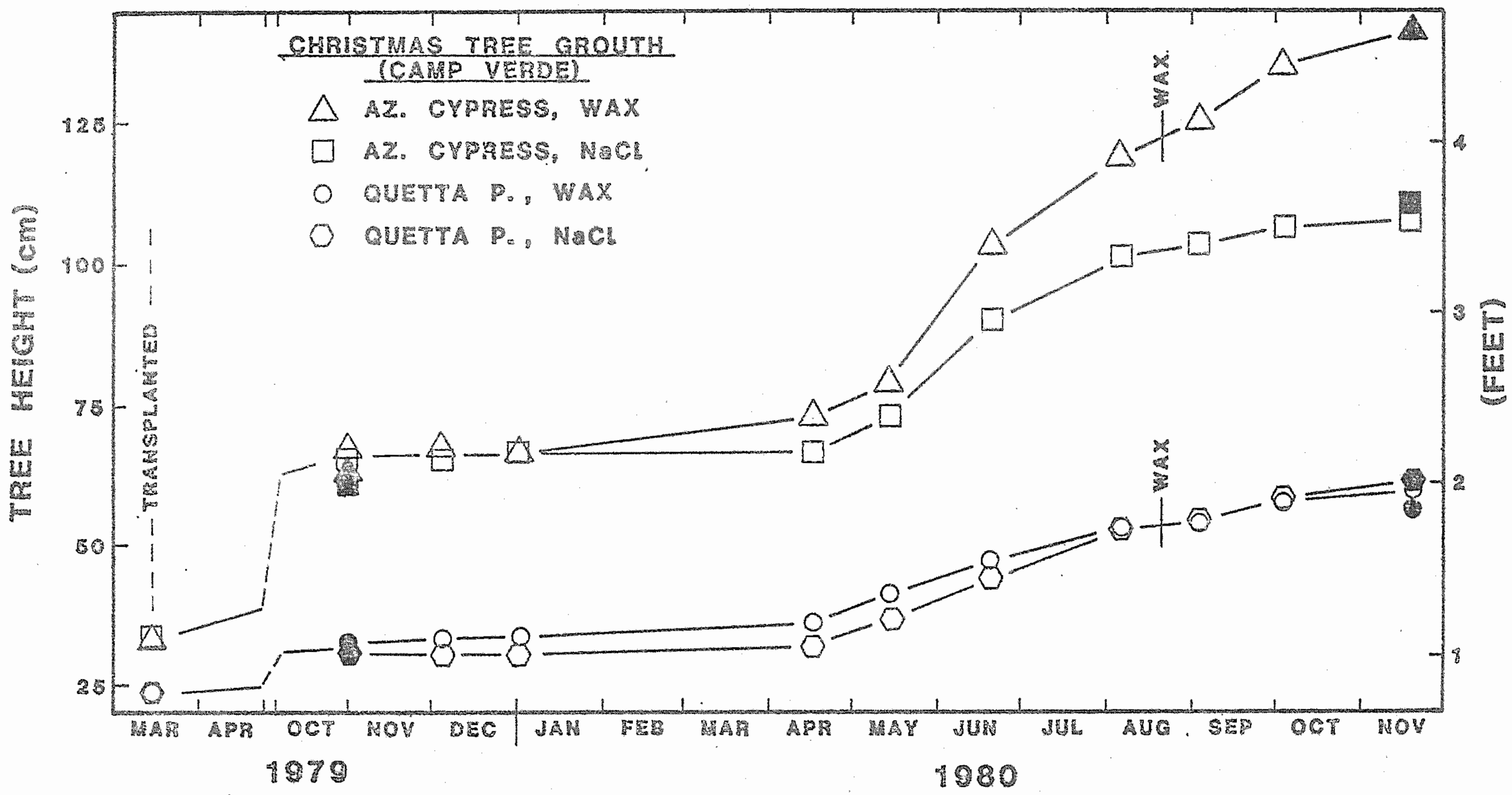

Figure 1. Christmas tree growth at two runoff farming sites at Camp Verde, Arizona. Shaded symbols are the average of all data for each tree type at each site; open symbols are the average of one tree from each replicate (each replicate has 5 trees) for each tree type at each site.

TITLE: COMPUTER SIMULATION OF GREENHOUSES

NRP: 20760 CRIS WORK UNIT: 5510-20760-003

SUMMARY AND CONCLUSIONS:

Additional progress was made toward the objective of evaluating the feasibility of closed greenhouses in arid environments using the modular energy balance (MEB) model. As described in previous Annual Reports, each module or subroutine simulates the performance of some energy-related device. Patterned after a TRYSYS program from the University of Wisconsin, the modular energy balance program is highly versatile because the user specifies at run time which of the devices he wishes to include in a particular run and how they are connected (wires and pipes) together. The program has virtually no size limit as implemented on the USWCL minicomputer because the subroutines are stored on the disk as overlay modules.

Several enhanced capabilities were added to the major subroutines which simulate the performance of the greenhouse itself. These included: (1) Curtain heat exchangers which save energy by utilizing natural rather than forced convection with fans. (2) A fluid roof which can absorb near-infrared radiation (which plants do not use for photosynthesis) before it enters the greenhouse. (3) Radiant heaters which can save energy by warming the plants directly and permit the greenhouse to operate at a lower air temperature, and (4) direct transfer of energy to a "soil" layer beneath the greenhouse so that the promising heat storage method developed at Rutgers, which uses water in a porous concrete floor, can be simulated. Another enhancement is currently being added which will make it possible to use thermal response factors for simulating soil heat flux. These factors have recently been developed by mechanical engineers as a method to increase the size of the stable time step and thus greatly decrease the amount of computation that must be done.

Also, additional new subroutines were written for simulating 1) flow tees; 2) a rock bed energy storage unit with latent energy exchange; 3) a multistage thermostat; 4) a curtain heat exchanger, and 5) a passive energy storage unit. The entire repertoire of modules now includes 1. reader, 2. integrator, 3. printer, 4. thermostat, 5. greenhouse, 6. fan or pump, 7. tee, 8. sensible heat exchanger, 9. sensible and latent heat exchanger, 10. solar collector, 11. storage tank, 12. time function, 13. reservoir, 14. complicated greenhouse, 15. simple greenhouse, 16. heater, 17. night sky radiation, 18. evaporative cooler, 19. rock storage with latent heat exchange, 20. arithmetic calculator, 21. multistage thermostat, 22. curtain heat exchanger, and passive storage unit.

With all the new additions, the publishing of the user's manual was postponed. At the present time it is complete except for describing the new additions to the complicated greenhouse and for examples of use of all the modules, but it should be ready to start the review process by midyear.

PERSONNEL: B. A. Kimball

TITLE: EFFECTS OF AIRBORNE PARTICULATES ON SOLAR AND THERMAL RADIATION AND THEIR CLIMATOLOGICAL CONSEQUENCES

NRP: 20760 CRIS WORK UNIT: 5510-20760-003

Work conducted under the aegis of this outline this year resulted in the preparation and/or publication of the following papers, which are briefly described below.

1. Idso, S. B. A set of equations for full spectrum and 8-14 μm and 10.5-12.5 μm thermal radiation from cloudless skies. Water Resources Research. (In press).

A comprehensive experiment was conducted at Phoenix, Arizona, involving the monitoring of full spectrum thermal radiation and those fractions of that flux that are contained within the 8-14 μm and 10.5-12.5 μm subregions. Also monitored were surface air temperature (T_o) and vapor pressure (e_o). Analyses of the data established the source of water vapor associated thermal emittance (ε) variations of the cloudless sky as being due to the variable atmospheric concentration of water dimers — pairs of water molecules linked together by weak hydrogen bonds. New equations based on this physical model were thus developed for the effective emittance of the atmosphere in both the 10.5-12.5 μm and 8-14 μm wavebands, as well as for the full thermal spectrum:

$$\varepsilon_{10.5-12.5} = 0.10 + 3.53 \times 10^{-8} e_o^2 \exp(3000/T_o)$$

$$\varepsilon_{8-14} = 0.24 + 2.98 \times 10^{-8} e_o^2 \exp(3000/T_o)$$

$$\varepsilon_a = 0.70 + 5.95 \times 10^{-5} e_o \exp(1500/T_o)$$

with T_o in degrees K and e_o in mb. The latter equation was then shown to be a significant improvement over previous equations that have attempted to model this phenomenon.

2. Idso, S. B. On the apparent incompatibility of different atmospheric thermal radiation data sets. Quarterly Journal of the Royal Meteorological Society 106:375-376. 1980.

Differences between measurements and calculations of atmospheric thermal radiation in different parts of the world were shown to be correlated with the dustiness of the air. This finding indicates how estimates of atmospheric thermal radiation may be improved by considering atmospheric dust concentration as a third independent parameter in addition to vapor pressure and air temperature.

3. Idso, S. B. On the systematic nature of diurnal patterns of differences between calculations and measurements of clear sky atmospheric thermal radiation. Quarterly Journal of the Royal Meteorological Society. (In press).

A reevaluation of previously published studies in light of the equation developed in reference (1) above showed that discrepancies between calculations and measurements of atmospheric thermal radiation were due to inadequacies of the formulations employed. The new equation of Idso appeared to resolve prior difficulties.

4. Idso, S. B. An experimental determination of the radioactive properties and climatic consequences of atmospheric dust under non-duststorm conditions. Atmospheric Environment. (In press).

A comprehensive experiment was conducted at Phoenix, Arizona, involving the monitoring of global solar radiation and 8-14 μm and 10.5-12.5 μm thermal radiation, as well as surface air temperature, vapor pressure, and dust concentration. Analyses of the data, which were all obtained under normal weather conditions, revealed that as dust concentration increases, the transmittance of the atmosphere for solar radiation decreases but the effective emittance of the atmosphere for thermal radiation increases. These analyses also demonstrated that the vertical redistribution of dust with season greatly alters the flux of thermal radiation to the surface, but has no effect upon the total solar flux to that level. These relationships were all numerically quantified and used to investigate the climatological consequences for the earth as a whole. It was demonstrated that the most probable effect of an increase in the atmospheric dust content would be a warming of near-surface air temperatures, due to a net increase in the radiant energy input to the surface.

5. Idso, S. B. A surface air temperature response function for earth's atmosphere. Boundary-Layer Meteorology. (Submitted).

A property of earth's atmosphere denoted the "surface air temperature response function" is shown to accurately represent the change in surface air temperature that is elicited by a change in radiant energy absorbed at the surface. It is experimentally evaluated by three independent techniques to yield a mean value over land of 122 K/cal cm^{-2} min^{-1}. Over the oceans, however, its value appears to be reduced by a factor of 2 or more.

6. Idso, S. B. The climatological significance of a doubling of earth's atmospheric carbon dioxide concentration. Science 207:1462-1463. 1980.

The mean global increase in thermal radiation received at the surface of the earth as a consequence of a doubling of the atmospheric carbon dioxide content is calculated to be 2.28 watts per square meter. Multiplying this forcing function by the atmosphere's surface air temperature response function, which has recently been determined by three independent experimental analyses to have a mean global value of 0.113 K per watt per square meter, yields a value of ≤ 0.26 K for the resultant change in the mean global surface air temperature. This result is about one order of magnitude less than those obtained from most theoretical numerical models, but it is virtually identical to the result of a fourth experimental approach to the problem described by Newell and Dopplick. There thus appears to be a major discrepancy between current theory and experiment relative to the effects of carbon dioxide on climate. Until this discrepancy is resolved, we should not be too quick to limit our options in the selection of future energy alternatives.

7. Idso, S. B. Carbon dioxide and climate. (A reply to critical "Letters to the Editor"). Science 210:7-8. 1980.

A number of questions relating to the work described in reference (6) are answered.

8. Idso, S. B. Human actions and nature's reactions. American Quaternary Association Abstracts. 6:105-106. 1980.

A critique of some recent doomsday climatic scenarios, particularly as pertaining to CO_2, is presented.

9. Idso, S. B. Surface energy balance and the genius of deserts. Archiv. fur Meteorologie, Geophysik, and Broklimatologie, Serie B. (In press).

A brief overview of numerical modeling approaches to the problem of desertification indicates that those techiques have generally ignored important surface boundary layer processes. A simple theoretical analysis of the surface energy balance clearly shows their shortcomings; and experimental data provide the basis for a new assessment of the land denudation phenomenon. It is shown that the mechanism invoked for desertification tendencies by the theoretical numerical models actually tends to suppress the formation of deserts; but that other neglected processes may indeed hasten their development, following vegetation removal by such processes as over-grazing.

10. Idso, S. B., and Cooley, K. R. Meteorological modification of particular air pollution and visibility patterns at Phoenix, Arizona. Archiv. fur Meteorologie, Geophysik und Bioklimatologie, Serie B. (In press).

Visibility data for the period 1968-1972 at Phoenix, Arizona were analyzed to show how variations among days of the week and hours of the day may be influenced by both pollutant source strength characteristics and meteorological phenomena. The results form the basis for future studies designed to decipher subsequent effects of technological modification of pollutant characteristics.

PERSONNEL: Sherwood B. Idso

TITLE: DEVELOPMENT OF REMOTE SENSING TECHNIQUES FOR AGRICULTURAL WATER MANAGEMENT AND CROP YIELD PREDICTION

NRP: 20760 CRIS WORK UNIT: 5510-20760-003

INTRODUCTION:

Research under this research outline in 1980 resulted in two published manuscripts dealing with instrumentation: use of hand-held radiometers and the design of a data-logger for those instruments. One manuscript is in press and two have submitted to journals concerning the stress-degree-day concept and the development of a crop water stress index. In the area of irrigation management, two manuscripts have been published and the third is in press. Relating foliage temperature to plant water potential in wheat and alfalfa has resulted in two manuscripts being submitted for publication. Evapotranspiration research resulted in two manuscripts being published and another in press. Two manuscripts have been submitted to journals dealing with the interpretation of spectral data from sugarcane and from Landsat. There have been three manuscripts prepared, one accepted by a journal and two recently submitted, that deal with the anatomy and morphology of barley. These were the result of work done by M. M. Paluska prior to her becoming a member of our research group.

In addition to the manuscripts listed above, five experiments were conducted in 1980 dealing with the use of remote sensing techniques for assessing crop stress. A cooperative research project was initiated with a farmer in the San Joaquin Valley of California (Westlake Farms) to develop a relationship between the crop water stress index and petiole water content of cotton for the purpose of scheduling irrigations. A unique lysimetric evapotranspiration micro-meterological experiment (LETME) was conducted from May to August 1980 where canopy temperatures and several micrometeorological parameters were measured at 11 locations in the United States, nine of which had precision weighing lysimeters. A mobile van from the University of California, Davis was used (they were cooperators on this venture) as it housed all the necessary equipment and computer for measuring, recording, and partially processing the various parameters. Several objectives were to be addressed on this trip: (1) evaluate various ET equations and compare them with the lysimeters; (2) evaluate the crop water stress index for various crops in different climates; (3) compare various shortwave and longwave models under various climatic regimes. The data is being processed, but two manuscripts have already used some of the data (#5, #9, below).

A major effort was expended in 1980 to rehabilitate our three precision weighing lysimeters. A chronology of events and the subsequent outcome are presented.

Serial Cereal, a multi-planting date experiment with Produra wheat was continued from 1979. The objective was to make daily spectral and thermal measurements of the crop, measure several plant parameters, and monitor micrometeorological and soil parameters and to relate remotely sensed information to crop growth, water stress, and yield. An experiment was conducted cooperatively with SEA/AR personnel in South Dakota to determine if foliage temperature of corn could be used to detect the infestation of the corn root worm. Cotton foliage temperatures were measured in Phoenix to evaluate their potential for scheduling irrigations.

PART A. INSTRUMENTATION

1. Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Idso, S. B. Hand-Held Radiometry. USDA SEA Agricultural Reviews and Manuals W-19, pp. 66. 1980.

Hand-held radiometers are small instruments that measure radiation that has been reflected or emitted from a target. Most have bandpass regions similar to those of scanners aboard satellites now in orbit or soon to be launched. Hand-held radiometers are particularly useful for obtaining frequent spectral and thermal data over numerous small plots having different treatments such as irrigations or fertilization. Such experiments allow the development of relationships between remotely sensed data and agronomic variables, as well as relationships needed for improved interpretation of satellite data and their applications to agriculture.

A set of notes was developed to aid the beginner in hand-held radiometry. The electromagnetic spectrum is reviewed, and pertinent terms are defined. View areas of multiband radiometers are developed to show the areas of coincidence of adjacent bands. The amounts of plant cover seen by radiometers having different fields of view are described. Vegetation indices are derived and discussed. Response functions of several radiometers are shown and applied to spectrometer data taken over 12 wheat plots, to provide a comparison of instruments and bands within and among instruments. The calculation of solar time is reviewed and applied to the calculation of the local time of Landsat satellite overpasses for any particular location in the northern hemisphere. The use and misuse of hand-held infrared thermometers are discussed, and a procedure for photographic determination of plant cover is described.

Some suggestions are offered concerning procedures to be followed when collecting hand-held spectral and thermal data. A list of references pertinent to hand-held radiometry is included.

2. Allen, R. F., Jackson, R. D., and Pinter, P. J., Jr. 1980. To relate Landsat data to U. S. Agriculture (formerly titled A microprocessor-based portable data acquisition system for hand-held radiometers). Agric. Eng. 61(11):12-14.

A portable, 8.5 kg, data acquisition system was designed to enable collection and rapid processing of radiance data from a four-band "Landsat Ground Truth" radiometer. After collection the data are dumped directly into a computer for processing with the results available 30 to 45 minutes after starting the measurements.

PART B. CROP WATER STRESS INDEX AND STRESS-DEGREE-DAY

3. Idso, S. B., Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Hatfield, J. L. Normalizing the stress-degree-day parameter for environmental variability. Agricultural Meteorology (in press).

Several experiments involving the measurement of foliage-air temperature differentials ($T_F - T_A$) and air vapor pressure deficits (VPD) were conducted on squash, alfalfa, and soybean crops at Tempe and Mesa, Arizona; Manhattan, Kansas; Lincoln, Nebraska; St. Paul, Minnesota; and Fargo, North Dakota. It is shown that throughout the greater portion of the daylight period, plots of $T_F - T_A$ vs. VPD yield linear relationships for plants transpiring at the potential rate, irrespective of other environmental parameters except cloud cover. This fact is used to develop a crop water stress index that is reasonably independent of environmental variability. Examples of its application to stressed soybeans and alfalfa are provided.

4. Jackson, R. D., Idso, S. B., Reginato, R. J., and Pinter, P. J., Jr. Canopy temperature as a crop water stress indicator. Water Resources Research (submitted).

Canopy temperatures, obtained by infrared thermometry, along with wet and dry bulb air temperatures and an estimate of net radiation were used in equations derived from energy balance considerations to calculate a crop water stress index (CWSI). Theoretical limits were developed for the canopy-air temperature difference as related to the air vapor pressure deficit. The CWSI was derived both mathematically and graphically and was shown to be equal to $1 - E/E_p$, the ratio of actual to potential evapotranspiration obtained from the Penman-Monteith equation. Four experimental plots, planted to wheat, received post emergence irrigations at different times to create different degrees of stress. Pertinent variables were measured between 1340 and 1400 each day (except some weekends). The CWSI, plotted as a function of time, closely paralleled a plot of the extractable soil water in the 0- to 1.1-m zone. Usefulness and limitations of the index are discussed.

5. Idso, S. B., Reginato, R. J., Jackson, R. D., and Pinter, P. J., Jr. Foliage and air temperatures: Evidence for a dynamic equivalence point. Agricultural Meteorology (submitted).

Experimental evidence is presented to demonstrate that the equivalence point of plant and air temperatures is not a universal constant in the vicinity of 33°C, as has long been tacitly assumed to be the case for well-watered vegetation. Instead, it is shown that the equivalence point is a dynamic variable, responding to both plant and environmental factors.

PART C. IRRIGATION MANAGEMENT

6. Jackson, R. D., Idso, S. B., Reginato, R. J., and Pinter, P. J., Jr. Remotely sensed crop temperatures and reflectances as inputs to irrigation scheduling. Proceedings of the Specialty Conference on Irrigation and Drainage - Today's Challenges. ASCE/Boise, Idaho, July 23-25, 1980. pp. 390-397.

Present irrigation scheduling techniques use soil and meteorological parameters to detemine irrigation timing and amounts. Remote sensing provides nondestructive direct measurements of crop canopy conditions that can be combined with the soil and meteorological information to improve irrigation scheduling. Remotely sensed canopy temperatures indicate crop water status. Coupled with a measurement of the air vapor pressure deficit, the canopy-air temperature difference offers a means of predicting when irrigation is needed based upon the plants response to its environment. Spectral reflectances are related to plant cover and plant density, and perhaps can be used to estimate the crop coefficients necessary to meteorologically-based computer scheduling techniques.

7. Jackson, R. D., Salomonson, V. V., and Schmugge, T. J. 1980. Irrigation management - future techniques. Proceedings of the Second National Irrigation Symposium, Lincoln, Nebraska, 20-23 October 1980 (in press).

The potential that remote sensing holds for irrigation management is largely undeveloped. Several facets of this potential have been demonstrated; for example, the determination of the areal extent of irrigated lands, the estimation of soil moisture, and the detection of crop stress. Full development of this potential, however, depends on aggressive research programs at all levels (ground, aircraft, and spacecraft platforms). Ground-based research, using instruments that are hand-held, boom-, or truck-mounted, offers a means of rapidly and frequently assessing a number of small fields of limited areal extent. Aircraft and spacecraft platforms enlarge the areal extent capabilities but usually decrease the frequency of measurements. At the present time, a serious limitation of satellite systems is the time delay between observation and data availability. A stringent requirement demanded by irrigation management is that data be available in near real time so that management decisions can be made soon enough to alleviate impending adverse conditions.

In this report we review some remote sensing techniques as to their usefulness in irrigation management. The visible and near-infrared, thermal infrared, and microwave regions of the electromagnetic spectrum are discussed in relation to agricultural parameters such as crop density, crop stress, soil moisture, and areal extent of irrigation. Satellite systems under development and in planning stages are discussed in terms of their usefulness for irrigation management.

8. Hatfield, J. L., Millard, J. P., Reginato, R. J., Jackson, R. D., Idso, S. B., Pinter, P. J., Jr., and Goettelman, R. C. 1980. Spatial variability of surface temperature as related to cropping practice with implications for irrigation management. Proc. of the 14th Annual Symposium of Remote Sensing of Environment. pp. 1311-1320.

Thermal infrared emission from a surface is a function of the surface temperature and emissivity. The temperature is dependent upon the energy partitioning and the surface features. For agricultural purposes the surface ranges from bare soil to complete vegetative cover. Studies have been conducted since 1976 at both Davis, California and Phoenix, Arizona using thermal infrared to measure crop stress. Crop stress has been evaluated with the stress-degree-day (SDD) concept which is a comparison of the midday canopy-air temperature difference. A canopy well-supplied with water is relatively cooler than air, whereas the leaves are warmer as the water availability decreases. Throughout the season the accumulation of SDD during the reproductive stage of growth is inversely related to yield. This relationship has been shown for durum wheat, hard red winter wheat, barley, grain sorghum and soybeans. SDD's can be used to schedule irrigations for maximizing yields. This concept can be used for applying remotely sensed data to management of water resources for optimum use of water.

To examine the variability in temperature that may exist from one agricultural field to another, and to determine realistic within-field temperature variations, an airborne flight with a thermal-IR scanner was conducted over a 50 km transect near the Sacramento Valley. The Texas Instruments RS-25 scanner had a 5 m pixel resolution at the flight altitude of 3300 m. Ground measurements of surface temperature, soil moisture and various agricultural parameters were acquired at various locations simultaneous with the overflight. An overlay displaying agronomic features was compared with the thermal imagery. Surface temperatures ranging from 22 to 45°C were correlated with these features; for instance, the 22°C surface temperature corresponded to wheat and barley fields and the 45°C temperature corresponded to fallow fields. Sharp temperature demarcations, as much as 16°C, occurred between many fields. Physical size of fields will thus place a limit on acceptable resolution of future spacecraft instruments. Temperature variations of about 5°C were noted within some fields, and this again will be important for determining the trade offs between a particular thermal-IR technique to be utilized and spatial resolution.

PART D. PLANT WATER POTENTIAL

9. Idso, S. B., Reginato, R. J., Reicosky, D. C., and Hatfield, J. L. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agronomy Journal (submitted).

Experiments were conducted to measure the air vapor pressure deficit and foliage-air temperature differentials of well-watered alfalfa at five different sites throughout the United States. At two of these sites data were also acquired for various degrees of stressed alfalfa, along with concurrent measurements of total plant water potential. The temperature and vapor pressure data were used to construct a plant water stress index which was related to the plant water potential. Different results were obtained for the two sites studied; but after a procedure was developed to remove variable atmospheric effects, the remaining soil-induced plant water potential depressions were found to be well described by a single function dependent upon the plant water stress index. These results demonstrate the ability of surface temperature measurement by means of infrared thermometry to rapidly assess large areas of cropped land for plant water potential depressions arising from shortages of soil moisture.

10. Idso, S. B., Reginato, R. J., Jackson, R. D., and Pinter, P. J., Jr. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. Irrigation Science (submitted).

Measurements of foilage and air wet- and dry-bulb temperatures were made over six differentially irrigated plots of Produra wheat grown at Phoenix, Arizona, in the spring of 1976. These data were used to evaluate a newly developed plant water stress index each day from the initiation of heading to the commencement of senescence. Total plant water potential data were also obtained daily over this period; and after demonstrating how to remove the atmospheric-induced component from these data, the resultant soil-induced component was plotted as a function of the water stress index. The result was a simple linear relationship, which was found to be identical to one recently derived for alfalfa. Finally, it was shown that grain yield was directly related to the mean plant water stress index over the reproductive growth period from heading to senescence.

PART E. EVAPOTRANSPIRATION

11. Idso, S. B. Evaluating evapotranspiration rates. Proceedings of the Deep Percolation Symposium. Arizona Department of Water Resources Report No. 1:25-36. 1980.

A brief history of methods for evaluating evapotranspiration rates is presented. The concept of potential evapotranspiration is then discussed, leading to the conclusion that plants always exert some degree of stomatal control over evaporative water losses from their leaves, unless they are wetted externally. This finding leads to the conclusions that (1) the presence of vegetation on or above the surface of an extensive lake or reservoir will tend to reduce the rate of evaporative water loss therefrom, and (2) irrigation by means of sprinkling is most effective when conducted at night. A brief synopsis of current work in the area of evapotranspiration assessment by means of remote sensing is then presented, along with a judgment on the future course of research required to expand this developing potential. Finally, a numerical example of calculating evapotranspiration rates by means of a new estimation procedure is presented.

12. Idso, S. B. Relative rates of evaporative water losses from open and vegetation-covered water bodies. Water Resources Bulletin (in press).

A review of the literature pertaining to the relative rates of evaporation from vegetation-covered and open water bodies is presented. The review indicates that the only reliable experiments capable of correctly addressing this question are those conducted in situ. Experiments of this nature show the ratio of vegetation-covered (swamp) evaporation to open water evaporation to generally be less than unity over extensive surfaces and to only approach unity for vegetation that is young and vigorous. Recent experimental evidence presented within a theoretical context, however, indicates that even in the latter situation the ratio may never reach unity. Consequently, over large lakes and reservoirs, the presence of vegetation may actually be a water conservation mechanism, with the eradication of the vegetation leading to significantly increased evaporative water losses.

13. Cooley, K. R., and Idso, S. B. Effects of lily pads on evaporation. Water Resources Research 16:605-606. 1980.

Measurements of evaporation from open water and water partially covered by lily pads have indicated that for the portion of the surface area covered by lily pads, evaporation is reduced to about 48% of that occurring from open water.

PART F. SPECTRAL RADIANCE

14. Jackson, R. D., Jones, C. A., Uehara, G., and Santo, L. T. Remote detection of nutrient and water deficiencies in sugarcane under variable cloudiness. Remote Sensing of Environment (submitted).

Spectral measurements were made in a red (0.63- to 0.69- μm) and an infrared (0.76- to 0.90- μm) band over sugarcane using a radiometer mounted on a 4-m aluminum pole. Infrared/red ratios measured over a plot with adequate nitrogen, potassium and water were significantly higher than those measured over a nitrogen-deficient plot at the 1% level, and higher than those over a potassium-deficient plot at the 10% level. In a second experiment, the infrared/red ratios of water-deficient plots were significantly lower than those for plots receiving adequate water. The measurements were made under conditions of variable cloudiness, ranging from full shade to direct sunlight. Although radiance values changed by a factor of 5 from one measurement to the next, changes in the infrared/red ratio were minimal, indicating that this ratio can be adequately measured under variable irradiance conditions for sugarcane when the plants form complete ground cover.

15. Malila, William A., Lambeck, Peter F., Crist, Eric P., Jackson, Ray D., and Pinter, Paul J., Jr. 1980. Landsat features for agricultural applications. Proc. of the 14th Annual Symposium on Remote Sensing of Environment, pp. 793-803.

This paper presents relationships among Landsat MSS-bands and selected transformations on them, with emphasis on the Tasseled-Cap Transformation and its Brightness, Greenness variables. It also discusses relationships between reflectance measurements made in the Landsat spectral bands and actual Landsat data. Agronomically oriented analyses of reflectance measurements of wheat throughout a growing season are presented, with a comparison of various green measures, correlation with crop development stage, and examination of the effects of moisture stress. The final example addresses the use of transformed variables in a newly developed approach to forestry change detection.

PART G. BARLEY ANATOMY AND MORPHOLOGY

16. Paluska, M. M. 1980. Effect of flag leaf and awn removal on seed weight of Arivat barley. Journal of Arizona-Nevada Academy of Science (accepted for publication).

The effect various plant parts have on final production, yield, is of special interest to plant breeders and physiologists. This paper presents data concerning the relative photosynthetic importance of flag leaves and awns to the final seed weight of barley. Awn removal reduced seed weight by an average of 19.4% in Arivat barley. Flag leaf removal reduced seed weight by an average of 3.3%. The effect of awn plus flag leaf removal appears to be additive, reducing seed weight by an average of 23.3%.

The data obtained here have prompted research utilizing a breeding program to develop a large awn population to supply germplasm sources for use by plant breeders and to supply additional research material for physiologists to continue investigations of the functions of awns in barley.

17. Paluska, M. M. 1980. The anatomy of the barley awn, lemma and palea. Crop Science (submitted).

Numerous research studies have demonstrated the importance of the photosynthetic activity in the cereal inflorescence, especially to seed weight. A research program designed to maximize the potential of the barley awn and other floral parts as photosynthetic structures, should be based on an understanding of the physiological function of these parts. And in order to understand function, the structure first needs to be described.

This paper presents a detailed description of the barley awn, lemma, and palea from 25 plant selections, made at random, from various composite cross populations grown in the field as part of the USDA Barley Genetics and Breeding Program, Tucson, Arizona. It also establishes the existence of variation in anatomical features among genotypes.

The observations from this study have prompted the development of a large awn population to supply germplasm sources for use by plant breeders and to supply additional research material for physiologists to continue investigations into the function of awns as photosynthetic structures.

18. Paluska, M. M. and Ramage, R. T. 1980. The morphology of barley spikes selected from a male sterile facilitated recurrent selection population for awn variation. Crop Science (submitted).

Researchers have shown that the awn is an important feature of the barley floret which contributes significantly to seed weight during the grain fill period. This experiment was designed to investigate the variation in awn and floret characteristics in a male sterile facilitated recurrent selection population. Fifty-four genotypes were selected at random from this population for awn variation. At anthesis, three primary tillers from each plant selection were measured. The average spike length, number of florets per spike, awn length, awn thickness, awn dry weight, and percentage of awn per spike were obtained. Spike length varied from 3.7 to 13.6 cm; number of florets per spike ranged from 26 to 94. Awn characteristics also displayed variation. Awn length varied from 3.8 to 18.4 cm; awn thickness ranged from .30 to .52 mm; awn dry weight ranged from .059 to .593 g; and the percentage of awn per spike varied from 25.5 to 58.7. This study demonstrates the existence of a wide range in the morphology of yield components among barley spike characteristics which could be exploited by barley breeders for yield improvement.

PART H. FIELD EXPERIMENTS

19. Westlake Farms, California

An experiment was conducted on cotton at Westlake Farms in the south San Joaquin Valley in California to determine if plant canopy temperatures could be used as an early warning indicator for the onset of stress due, in this case, to inadequate soil moisture. In addition, a comparison was to be made between the newly formulated crop water stress index and petiole water content, the latter having been proposed as a guide for scheduling irrigations.

The experiment was conducted at Westlake Farms for several reasons. First, we wanted to evaluate the use of the crop water stress index on a commercially operated farm so as to be able to determine what problems would be encountered in actual practice. Second, the grower had made a commitment to the project by purchasing an infrared thermometer and by hiring a student for the summer solely to collect data. Third, we would be involved only in setting up the experiment and analyzing the data, and its conduct was left to the grower. Fourth, the field plots were to be large (4.1 ha or 10 acres each), rather than the small plots (0.02 ha or 0.05 acres) we normally used.

The experimental plots were located at 36° 07' 30" North and 119° 53' 38" West on the east 1/2 of Section 8, Township 20 South, Range 19 east. The soil is Tulare clay (Typic Haplaquent, fine montmorillinitic, calcareous, thermic). Three replicates of three irrigation treatments of Acala SJ-2 cotton were planted on 2 April 1980. Each of the nine borders contained 66 rows planted in an east-west alignment on a 0.76 m (30") spacing and was 804 m (0.5 mile) long. Each plot contained 4 ha (10 acres). Surface water was pumped onto the plots when required at the rate of 280-850 l/s (10-30 cfs) for an application of 10 cm of water.

The three irrigation treatments were to be irrigated as the grower normally did (four irrigations after the preplant application), one treatment was to receive an additional irrigation (5) to keep transpiration at or near the potential rate, and one was to receive only three irrigations to attempt to develop some plant stress. Table 1 gives the irrigation dates for all plots.

Plant canopy temperatures were taken six days per week with a Telatemp AG-42 infrared thermometer (serial number 388) from 25 June 1980 through 30 August 1980, with the exception of two weeks in early August when the unit was being repaired. Eight canopy temperatures were measured on each border: four looking north across the rows and four looking south across the rows. The readings were spaced 15 m (50') apart starting from the east side of the border. Air wet- and dry-bulb temperatures were taken with a Bendix aspirated psychrometer between each border, 60 m (200') in from the east border. Daily visual observations were also made of sky conditions and general plant health.

A weather station was set up at Westlake Farms headquarters about six miles north of the experiment. The station included a recording hygrothermograph, maximum-minimum thermometers (read daily), an anemometer for total wind run (read daily) and a pyranometer with a recording integrator to give daily values of incoming solar radiation.

Petiole water content was proposed (in 1969) as a parameter which could be used as a guide for scheduling irrigations. The technique is time consuming, so the comparison of using the infrared thermometer with petiole water content was desirable.

Petioles were obtained by pulling the uppermost mature leaves from randomly selected plants across each replication. Leaves were then stripped from the petioles in the field, and the petioles were placed in sealed plastic bags until weighing and drying (later that same day). Samples were taken approximately three times weekly.

<u>Results for Westlake</u>

Petiole water content (PWC) is plotted as a function of date in Figure 1 for all three treatments. The value for any point is the average of the three replicates. The criteria established previously by the grower was to irrigate when the PWC reached about 0.84 (which was done for the wet treatment). There are periods of missing data, but the trends are clear. Early in the season the PWC was high (0.88) and declined until an irrigation. After watering the PWC did not recover to its high value of 0.88 but only to 0.87 after the first irrigation and to 0.84 to 0.85 for subsequent irrigations. It is also of interest to note that the rehydration process was not complete until a week after the irrigation, indicating an internal adjustment period for the crop and time for the water to be distributed within the root zone.

From these data it was assumed that the cotton was transpiring at the potential rate when the PWC exceeded 0.86. To establish the lower baseline for cotton of the foliage-air temperature differential - vapor pressure deficit relationship, only those data collected on clear days when the PWC >0.86 were used. Figure 2 shows the relationship. The upper limit of $T_F - T_A$ was obtained from the technique proposed by Idso et al (item #3 in this report).

Using the upper and lower limits in Figure 2, a crop water stress index (CWSI) was calculated (per Idso et al, #3) for all days where PWC data were available. Also, a CWSI was calculated for the same days from a theoretical approach described by Jackson et al (item #4 in this report). This latter CWSI requires, in addition to foliage temperature, and air wet- and dry-bulb temperatures, an estimate of net radiation at the time of foliage temperature measurement. These estimates were made from an earlier study relating the daily total solar radiation to an instantaneous solar radiation value about an hour after solar noon and then taking 0.75 of that latter value.

The two crop water stress indices are plotted as a function of date in Figure 1 for the three irrigation treatments. In spite of the gaps in data, the trend is clear: as the PWC increases after an irrigation, the CWSI decreases, indicating that the crop is rehydrating. These two independent measurements of plant stress appear to be somewhat in phase during this 60-day measurement period for cotton. The arrows at the top of each graph in Figure 3 represent 10 cm irrigations for the three treatments. Both crop water stress indices follow quite similar patterns, although Idso's has a larger amplitude than Jackson's.

A plot of CWSI vs PWC is shown in Figure 3 for both methods of calculating the index. Although the slopes and intercepts are different, the regression coefficients are nearly identical, indicating that both methods of calculating the CWSI work equally well for this set of data.

In 1977, personnel from Westlake Farms conducted an experiment on cotton where they tried to use petiole water content as a guide to schedule irrigations. They found an inverse relationship between yield of lint cotton and the average petiole water content during the growing season. The data from 1980 showed a similar trend and is displayed in Figure 4 along with the 1977 data. There are too few data to determine the exact shape of the relationship, but the trend is quite clear. The highest yield was obtained when the average petiole water content was >0.86. These data also indicate that allowing the PWC to decrease only slightly will result in a significant yield reduction.

Also plotted in Figure 4 are both CWSI's. No canopy temperature data were taken in 1977, so only 1980 data are shown. Both indices were averaged over the same measurement period as the petiole water content (27 June - 15 August 1980) and plotted as a function of yield. The relationship between the indices and yield are very similar although displaced one from another. They are also very similar to the PWC-yield relationship for

1980. This implies that both the CWSI and the PWC are good predictors of cotton lint yield.

SUMMARY:

An experiment on cotton was conducted in the south San Joaquin Valley of California entirely by the farmer during the summer of 1980 to determine if foliage temperatures could be used to schedule irrigations. He also measured petiole water content frequently as he determined from previous research that this parameter could be used for irrigation scheduling. The data were collected by the farmer and processed by us.

The crop water stress index follows, in an opposite fashion, the petiole water content as a function of time. As the plant dehydrates, due to lack of soil moisture, the PWC decreases and the CWSI increases. Because of the limited data set over several irrigations the whole season picture is incomplete. However, the trend is clear: the CWSI is reasonably well correlated with PWC ($r^2 = 0.53$). Also, the results show that both the average petiole water content (PWC), and average crop water stress index (CWSI) are good predictors of cotton lint yield. Additional research will be conducted in 1981 at Westlake Farms and at Phoenix to verify the CWSI-PWC relationship and to investigate how the CWSI can be used to schedule irrigations for cotton.

20. LETME

A Lysimeter Evapotranspiration Micrometeorological Experiment was conducted during June and July 1980 at 11 research locations in the United States. The purpose of this project was to evaluate the stress-degree-day concept and the crop water stress index on different crops under different climatic regimes. Since nine of the eleven locations had precision weighing lysimeters, data were collected to evaluate several evapotranspiration models for comparison against lysimetric data. In addition, various shortwave and longwave radiation models were to be evaluated under the various climatic regimes. The locations visited and crops observed are listed in Table 2 in the order of visitation. The locations varied in latitude from 26°N to 46°N, in longitude from 93°W to 121°W, and in elevation from -30 m to 3337 m, a wide range of conditions. Weather conditions were quite good and there was at least one completely clear day at each location.

The trip was accomplished using a mobile van from the University of California, Davis which housed all the necessary equipment and computer-based data acquisition system. Drs. Jerry Hatfield (UCD), Sherwood Idso (USWCL) and Robert Reginato (USWCL) were the data gatherers on the trip. All instruments were calibrated prior to and immediately following the nine-week trip. A unique feature of the trip was that all data were collected in a nearly identical manner at all locations and the instruments and setups were identical at all locations. Table 3 lists the types of sensors used, where they were located, and the frequency of measurement for each sensor.

All the manually obtained data have been entered in the computer so it can be processed in conjunction with the micrometroeological data. All of the data are currently being analyzed to meet the objectives of LETME. Two manuscripts have been written (items 5 and 9, above) using just a small part of the data. Next year's Annual Report will have more on LETME.

21. LYSIMETER REHABILITATION

The lysimeters have not been operational for about four years, so it was decided to repair them. The decision to repair them was based on the fact that a comprehensive experiment to be initiated late in 1981 require precise short time measurements of evapotranspiration.

On 16 June 1980, the inner bins were removed and the load cells were removed. We attempted to install recently purchased load cells, but found they were the wrong size. New load cells (the correct configuration) were ordered and delivered in August. They were installed, and the inner bins replaced. But the lysimeters could not be calibrated. It was noticed that the counterweights were not centered in the counterweight shaft of lysimeter 2. We then decided to excavate all three lysimeters and have the weighing mechanism (coffin) repaired by a local scale company.

The counterweights and inner bins were removed prior to excavating the remainder of the lysimeter system. The top six inches of soil around each lysimeter was removed and kept in a separate pile for repacking purposes. Soil was excavated about 40 cm below the top of each concrete support system. The counterweight shafts and outer bins were then detached from the coffin and moved to the side of the field. Last, the coffins were removed for inspection. The rear baskets and front end cover plates were removed to expose the weighing mechanism.

Rust covered the interior walls and balance beams of all three lysimeters, and there was about 2 to 5 cm of rust particles on the bottom of two coffins. The third coffin had about 5 cm of soil deposited in it.

All moving parts in all three lysimeters were either immobile or out of alignment. Southwestern Scale Company of Phoenix took lysimeter #3 coffin to see if it could be repaired. After dismantling this unit, it was found that the upper horizontal flexure had failed. All other parts were only rusty. The company sandblasted and painted all components, reinstalled them (with a new flexure), and returned the coffin to us for testing.

The coffin was placed on temporary supports on the pavement, the new load cells mounted in place, and the inner bin and counterweights installed. Weights were added to the counterweight shaft until the balance beam was free. This was observed by noting the movement of the end of balance beam between the two mechanical stops behind the end plate (which was removed). Once the beam was in balance, a quick calibration was made to determine if full scale (50 kg) could be obtained. The calibration was successful.

After this calibration the inner bin and counterweights were removed, and the basket and end plate were reinstalled sealing them with silicone rubber around the bolts. The company proceeded with repairing the other two coffins.

While the other two coffins were being repaired, the three inner bins were saturated with tap water (400 ppm total salts), and vacuum pumps were connected to the extraction units. The initial salt content of the extracts were 5,800 ppm, 8,200 ppm, and 12,600 ppm for lysimeters 1, 2, and 3 respectively. Lysimeter 1 yielded 35 to 55 liters/day during the next month (tap water was added occasionally to the soil surface during the month and the salt content of the extract was reduced to 765 ppm. Lysimeter 2 yielded 25-25 liters per day and the salt concentration declined to 1050 ppm. The problem was with lysimeter 3. The extraction units clogged and only 4-8 liters/day could be removed. In a month's time the salt content declined only to 8000 ppm. Four ceramic cups were installed from the top of the soil to the bottom of the tank with the hope of increasing the extraction of salty water from the bottom of the lysimeter. This procedure was not very satisfactory. The soil around the cups was probably dispersed during installation and the hydraulic conductivity was decreased drastically. The vacuum pump is still running at the writing of this report (14 April 1981), and the salt content has been reduced to about 5000 ppm.

The three repaired coffins were placed in the concrete footings and leveled. Silicone rubber was beaded on each coffin where the counterweight shaft and outer bin would rest on it for waterproofing purposes. After placing the outer bin and counterweight shaft in place, the load cells were installed and connected to the power and signal cable.

In order to prevent water from getting between the coffin and concrete footings, a single rubber sheet, with cutouts for the counterweight shaft and outer bin, was installed. The sheet was attached to the bin and shaft about 40 cm above the coffin. This was accomplished by pressing the sheeting against previously installed caulking tape. The sheeting was held in place using pine 2 x 4's and metal strapping. About 3 cm of sheeting stuck up above the 2 x 4's and was filled with silicon rubber. The rubber sheet draped over the edge of the concrete footing so no water could enter the footing.

In the event that water somehow managed to get in the footing, a one-half inch copper tube was placed between the coffin and footing to facilitiate water removal. Similar tubing was placed in the coffin in the event that water entered the coffin.

The inner bins were reinstalled, counterweights added to bring the system in balance, and a calibration performed. All systems worked perfectly.

Air dry soil was backfilled around the lysimeters and tamped in with a soil compactor. The last 15 cm of soil was hand packed to avoid pulverization.

The outer bins of lysimeters 1 and 2 shifted slightly and rubbed the top edges of the inner bins. A small pry bar was used to remedy the problem and a final calibration was made on all three lysimeters (Table 4). As of this date (14 April 1981) all lysimeters are working as well as the day they were initially installed in December 1960.

22. Serial Cereal

The second consecutive year of a staggered planting date/water stress experiment in wheat was concluded in May 1980. This report will provide a brief overview of these experiments, termed Serial Cereal I and Serial Cereal II to refer to planting dates within the 1978-79 and 1979-80 growing season, respectively. First broad research objectives will be outlined and details of the experimental design and the types of agronomic, meteorological and remote sensing measurements are described. Preliminary results, which will serve as a basis for more detailed analysis in the coming year, will be presented.

Research Objectives

Serial Cereal I and II were designed to provide a continuous cropping experiment wherein it would be possible to acquire an extensive data base of reflected multispectral and emitted thermal radiation from wheat canopies of varying biomass levels and stages of growth. This was deemed necessary to assess the utility of various remote sensing techniques in the detection of water stress under varying seasonal climatic conditions. It would also enable separation of seasonally-induced changes in remotely-sensed information from those caused by differing phenological growth stages and canopy densities.

Among the secondary objectives of these experiments, we sought a solution to the partial canopy problem which complicates the interpretation of downward viewing thermal scanner data from aircraft and satellites. We have shown that plant temperatures are sensitive indicators of water stress and thus are useful in the scheduling of irrigations and prediction of yields. Yet under less than full canopy cover conditions, background soil temperatures also contribute to the radiant energy measured by instruments viewing in a nadir direction. If uncorrected for the radiant energy received from soils, these temperatures would lead to serious errors in estimation of plant stress.

Radiant temperatures and reflected visible and near-IR light are strongly dependent upon the bidirectional properties of a crop canopy. These in turn, are a function of canopy geometry and row orientation. Serial Cereal I and II provided us with as many as five different stages of growth at several different water stress levels which could be compared simultaneously under the same illumination angles. On ten separate dates during these experiments the diurnal course of spectral reflectance was measured for each planting date.

Spectral reflectance measurements were made over each plot beginning at planting and continuing until the vegetation reached senescence, using a 4-band hand-held Exotech Model 100-A radiometer. This instrument has band-pass characteristics similar to the multispectral scanner (MSS) on board LANDSATs 1, 2 and 3 (i.e., MSS4, 0.5 to 0.6 μm; MSS5, 0.6 to 0.7 μm; MSS6, 0.7 to 0.8 μm; and MSS7, 0.8 to 1.1 μm). During SC I, measurements were made as often as three times per day: 1) at solar noon; 2) at 0930 h MST; and 3) at a nominal solar elevation of 33°. During SC II measurements were made at 1) a solar elevation of 33° and 2) at 1340-1400 h MST, the time of oblique and down radiant plant temperature measurements. The data collection routine consisted of frequent measurements of a horizontally positioned $BaSO_4$ reflectance panel, a measurement of wet and dry soil radiances and a series of measurements over each of the experimental wheat plots.

Basic plant parameters were measured during both experiments. Plant density was determined by enumeration of seedlings in the pre-designated harvest areas, and also at the time of harvest by digging up clumps of plants and carefully teasing apart the roots of individual plants. Throughout the season, six plants were sampled at random, twice a week from destructive sampling areas indicated in Fig. 5. The main stem of each plant was staged according to the Feekes scale, the number of live stems counted and the total length of the plant from the soil surface line to the tip of the longest mainstem leaf was measured. After obtaining a wet weight on the above ground plant parts, the total number of expanded, ≥50% green plant leaves was determined. The green leaf area was then measured on an optically-integrating area meter (Lambda Instruments Corporation, Model LI-3100, 1.0 mm^2 resolution), followed by green stem area and the brown stem and leaf area combined. Green and brown flag leaves were measured separately. Beginning with Feckes stage 9 (the ligule of the last leaf just visible, ear swollen and awns visible), the heads were dissected from the stem, and their wet and dry weight obtained. Then the number of stems greater than stage 9, stage 10.1 (mainstem ears just visible) and stage 10.5 (head above ligule, or in the case of drought-stressed plants, completely split through the leaf sheath) were determined. Total dry biomass was obtained after plants were dried in a ventilated oven at 70°C for a minimum of 48 hours. Approximately 60-80 manhours per week were required to process 240 plants samples per week during the peak period of Serial Cereal I, and 40-60 manhours for 204 plants/week in Serial Cereal II. Plant sampling continued from emergence until one week after plants reached stage 11.4 (grain ripe, straw dead).

In a separate operation, plant heights (from the soil surface to the tip of the highest plant element) were measured in situ three times weekly. Both vertical and oblique photos were taken at 7-10 day intervals of the target areas of each plot.

At harvest, the number of heads per m^2, and threshed dry grain yield per m^2 was determined for each of the four harvest areas within each plot ($\sim 13\ m^2$).

Experimental Design

Serial Cereal I and II were conducted on the backyard field plots of the U. S. Water Conservation Laboratory during the 1978-79 and 1979-80 seasons. The laboratory is located at Phoenix, Arizona (33°26'N, 112°01'W). The light colored soil is classified an Avondale Loam (a fine loamy, mixed [calcareous], hyperthermic Anthropic Torrifluvent).

The field layout (Fig. 5) enabled each plot to be irrigated separately on very short notice with city water (about 400 ppm total salts) using layflat irrigation tubing. Plots averaged 176 m^2 in size and consisted of destructive plant sampling areas and "final harvest" areas which were not disturbed during the growing season. Thermal measurements were concentrated around these harvest areas on both sides of the E-W access boardwalk. Reflectance measurements were restricted to designated target areas within the harvest areas on the south side of the boardwalk (labeled EX in Fig. 5). This minimized the possibility of shadow interference with the observations. During Serial Cereal II the two target areas in each plot were doubled in size to 1 x 3 m. A neutron access tube (* in Fig. 5) was positioned in the center of each plot (18" south of the boardwalk) during SC I and left in position for the following year's experiment. Soil moisture measurements by the neutron scattering technique were made three times a week in 20-cm increments to a depth of 160 cm. Each plot was also instrumented with a net radiometer and an inverted pyranometer at a height of 150 cm above the soil surface. Air temperatures were measured at 150 cm and 15 cm; soil temperatures at -2 cm and -5 cm. Incoming solar radiation, wind speed and direction, and vapor pressure at 150 cm (LiCl dewcell) were measured at one location for the entire field. Meteorological parameters were scanned at the rate of 2 per second by an automatic data logger located in a cabin at the north edge of the field. The mean values for each parameter at the end of each 20-minute period were recorded on a magnetic disk via real-time hookup to a computer located in the main laboratory building.

Thermal IR measurements were made every non-raining workday between 1340 and 1400 h (MST) using a Telatemp AG-42 infrared thermometer (4° F.O.V., 10.5 - 12.5 µm). During SC I, four measurements (two viewing east, two west) were averaged for each subplot. The thermometer was held so that it viewed each canopy obliquely (ca 30° from the horizontal) and at right angles to the N-S row direction. This minimized the effect of background soil temperatures when canopy cover was less than 100%.

During SC II the measurement routine was expanded to include eight repetitions of the oblique temperature observation (4 east, 4 west). In addition a 20° F.O.V. infrared thermometer (Barnes PRT-5) was used in a nadir-oriented fashion in both the SE and SW target areas (12 measurements per plot). This was to simulate temperature which might be obtained from a scanning device on board aircraft or satellites. Calibrations of each infrared thermometer were performed every 3-6 weeks on a precision laboratory calibration device; a routine 2-temperature calibration check was performed before and after each set of field measurements.

Agronomic Results

Table 5 summarizes the cultural operations rainfall and irrigation amounts for both experiments. During Serial Cereal I, field preparation consisted of pre-irrigating the entire field, then fertilizing, cultivating and planting a north-south border (e.g., 1A, 1B, 1C, 1D) by tractor on the indicated date. Instruments were installed in 2-4 days and the crop irrigated up. Plots were rototilled and planted by a single wheeled manual planter (usually 4 weeks after a preirrigation) during the second experiment. This was to avoid tractor compaction of the soil and eliminate the need to reposition the meteorological instruments and neutron access tubes. Plots were generally irrigated within 24 hours after planting.

Seeds were planted at a depth of 2 cm in north-south oriented rows. No herbicides were used during the experiments; when required, weeding was accomplished by hand. A total of 37 separate plots of Produra wheat (Triticum aestivum Desf. var Produra) were planted at ten dates from 31 October 1978 until 6 February 1980 (Table 5). A 23 August 1979 planting was attempted in plots 1A, 1B and 1C, but emergence was so poor it was replanted during late September 1979.

Irrigation scheduling was accomplished by a variety of methods, including the volumetric soil moisture contents, the stress degree day concept and traditional calendar scheduling. Early in the growing period we assigned a wet, a dry and two intermediate levels to plots of given planting date. Typically the wet plot received what we considered an optimum water supply. Since we were most interested in a simultaneous comparison of well-watered and drought-stressed plots we often timed irrigations to achieve that goal.

Individual plots were usually irrigated separately, with 8-12 cm of water being applied at each irrigation. Plots received differing amounts of irrigation water and rainfall totaling 21 to 100 cm of water.

Planting date 5 (Serial Cereal I) received a great deal more water than usually required to grow a crop of wheat. As many as 11 irrigations were given to these plots in an attempt to promote stand establishment and fill grain kernels during the hot spring and summer months.

The length of time for the crops to complete their life cycles when planted at different dates is shown in Figures 6. The extreme left of each bar corresponds to the date of planting. Alternating segments of the bar designate the duration of each major developmental period based on the Feekes scale of wheat phenology (Large 1954). From left to right these are: 1) planting to emergence; 2) tillering; 3) stem extenstion; 4) heading; 5) flowering; and 6) ripening. The small tic marks along the upper margin of each bar represent timing of irrigations with respect to phenological development. Because the normal consumptive use of spring wheat in Central Arizona is ca 60 cm of water and since rainfall was above normal during the winter months of both years, it was possible to produce an acceptable crop with only one post-planting irrigation. The rainy periods prevented the development of drought stress during certain times despite our efforts to set up different levels of soil moisture availability through staggered irrigations.

The suggested time for planting spring wheat in Central Arizona is between 15 November and 15 December. Our data show that the time required for development of a crop planted within that window is from 150 to 170 days (Figure 7). A crop planted then, typically takes 10-12 days for emergence, 60 days for tillering, 35 days for stem extension, 30 days to complete the heading and flowering process, and 25 days for ripening. Crops sown earlier required a more lengthy period for development (up to 185 days) while those planted late in the spring only needed 80 days until harvest. Although the most important factor influencing the duration of a particular phenological stage was probably temperature, we observed that moisture stress accelerated crop development slightly; the driest plots became ready for harvest about 7-10 days before those irrigated more frequently. The data in Figure 7 imply that a simple model based on growing degree days or even calendar date would be sufficient to predict crop phenology over a wide range of planting dates.

The final grain yield of the experimental plots ranged from 1 to 554 gm^{-2} (Table 6, Fig. 8). Crops planted during the optimum planting period produced acceptable yields provided they received adequate moisture during the growing period. Earlier or later plantings often resulted in very low yields even though large amounts of water were supplied by frequent irrigations. Low yields were a result of a number of factors. During Serial Cereal I, for example, stand mortality due to high temperatures was appreciable in plots 4 and 5 despite irrigations which totaled as much as 100 cm of water. A comparison of plant density counts at emergence and harvest showed that essentially no mortality occurred during other planting dates. Flowering is a stage that is particularly sensitive to temperature stress. Note that plots 4 and 5 (Serial Cereal I) had fairly low seed counts per head. This was probably a result of high temperatures during anthesis. Similarly, plot 1 (Serial Cereal II) had a low number of seeds per head. These plots were flowering during January and cold temperatures may have caused less grain to be set. Ripening, however, took place under more favorable conditions and the individual seeds were larger than those recorded for any other subplot.

Certain stages are more susceptible to water stress than others. During Serial Cereal II, for example, subplots 3A, 3B and 3C each received about 35 cm of water. Subplot 3B, however, was the only one to receive a preplant irrigation (2 months earlier) as well as an irrigation during the grain filling stage. As a result, its yield was 80% higher than either 3A or 3C (its average seed weight was 30% higher).

22. Cotton 80

In 1980, research was conducted to determine the feasibility of using IR-thermometry for monitoring plant water status and scheduling irrigations in Upland cotton. The experiment was conducted on a 2 ha field located on the University of Arizona, Cotton Research Center farm in Phoenix. The Water

Conservation Laboratory remote sensing work was designed in conjunction with a pre-existing experiment implemented by Drs. Gene Guinn, Jack Mauney and Kenneth Fry, Plant Physiologists at the Western Cotton Research Laboratory at Phoenix. Their primary objective was to examine the effect of different early season water management options on plant growth and physiological parameters.

Briefly, the experiment consisted of six repetitions of six different early season irrigation treatments. The first post-planting water application was staggered at 1-week intervals, beginning in late May. Treatments A and F were irrigated at that time; treatment B, 1 week later; treatment C, 1 week after that and so forth. Although the second irrigation for treatment F was delayed until mid-July, irrigations for all other treatments were given at 14-day intervals after the first water application.

The remote sensing measurement routine included once-a-day (1330 h MST) observations of plant leaf and plant canopy temperatures using a portable handheld infrared thermometer (10.5 - 12.5 μm, 4° F.O.V.). Leaf temperatures were obtained by aiming the thermometer at individual, fully expanded leaves at the top of the canopy. Eight measurements were averaged to obtain a mean for each of 12 plots (2 repetitions, 6 treatments). Canopy temperatures were estimated from measurements taken with the IR-thermometer pointed obliquely towards the crop (about 30° from the horizontal) and at right angles to the E-W oriented rows. An average of 4-north and 4-south viewing observations was taken. Routine meteorological data were also collected. These included start and finish wet and dry bulb readings from an aspirated psychrometer held at a height of 150 cm within the field, sky conditions, cloud type, cloud cover, haze levels, wind speed and incoming solar radiation. Average row width and plant height data were recorded twice weekly. A measure of canopy cover when viewed at an oblique angle was estimated by holding a 5 cm diameter cylinder at arm's length pointing it at the canopy at the same angle as the infrared thermometer and then qualitatively estimating the proportion of green canopy included within its viewing field. Photographs were taken at weekly intervals. More detailed plant growth and physiological measurements were conducted at intervals by Western Cotton Research Laboratory personnel.

Early in the season, when cotton plants were relatively small and canopy cover was sparse, canopy temperatures T_c were often 15-20°C higher than leaf temperatures T_l. This was especially evident when the soil surface conditions were dry; the difference was less when soils were in the intermediate stage of drying. The difference between T_c and T_l was minimal for a day or so following an irrigation. As canopy cover increased later in the season, T_c and T_l were generally within ±1°C. Due to the staggered early irrigations, the date when T_c and T_l became similar was variable. We found that it varied from the last week in June to the third week in July. At the time T_c and T_l converged, an average plant was 55 cm high and 48 cm in width. When viewed at an oblique angle about 90% of an infrared thermometer's field of view had to be plant material before the effect of background soil temperatures could be ignored. Thus, prior to the time when oblique canopy cover reaches 90%, actual leaf temperatures should be used in scheduling irrigations. As an alternative, an algorithm relating T_c to T_l under varying cover and soil moisture condition appears to have some promise.

To examine whether IR thermometry is feasible for monitoring changing trends in crop ET induced by irrigation cycles, we transformed the T_l and T_c data into the crop water stress index proposed by Idso et al (1980). First a subset of T_c and T_l data was extracted from the entire data base and a relationship was developed between the T_l (or T_c) minus air temperature and the vapor pressure deficit (VPD) of the air. This subset of data was selected from plots known to be well watered (i.e., 3 to 9 days following an irrigation during midseason and 3 to 6 days later in the season). Further criteria for these data required that there was no cloud interference with direct beam solar irradiance, mostly clear skies and relative low winds. All data were from plots which had reached the ≥90% "oblique" canopy cover level.

The well-watered baselines calculated for T_c-T_a and T_l-T_a versus VPD for cotton were:

$$T_c - T_a = 0.70 - 0.16\ (\mathrm{VPD}) \qquad r = 0.67^{**} \qquad (1)$$

and

$$T_l - T_a = 0.30 - 0.17\ (\mathrm{VPD}) \qquad r = 0.63^{**} \qquad (2)$$

where T_c and T_l are uncorrected for canopy or leaf emissivity, T_a is the air temperature at +150 cm and VPD is expressed as mb vapor pressure deficit at +150 cm.

The season-long trend of the CWSI based on T_l is shown for two representative treatments (Fig. 9). Although in theory this index should vary from 0 to +1 as a crop advances from well-watered to drought-stressed status, in practice these boundaries are exceeded due to the inherent variability of baseline data (Eqn. 1 and 2) and the variability about the upper limits which a low-transpiring crop would be expected to attain. Note that the CWSI follows a cyclical pattern that appears synchronous with irrigation events (arrows). Almost immediately following an irrigation the CWSI falls to a minimum value then climbs slowly as the crop exhausts its supply of water. The rate at which the CWSI increases between irrigations is directly related to the atmospheric evaporative demand and the size of the plants. It is inversely related to the amount of water stored in the soil and its availability to the plants. In addition, Figure 9 illustrates that for early season canopies the CWSI does not return to low levels following irrigations even when T_l is used instead of T_c. It appears that small cotton plants are more closely coupled to their thermal microenvironment than larger plants. With so much hot soil surrounding the plants, the thermal radiation probably contributes considerably to the energy balance of individual leaves. It is likely that a different baseline will be required for non-stressed plants early in the season.

Several additional problems emerge when daily CWSI values as shown in Figure 9 are used to schedule irrigations. First it is not known to what level the CWSI should be permitted to reach before water stress imposes a yield reducing effect. Cotton is different from certain other crops in that optimum water management requires moderate amounts of stress at critical periods to ensure optimum boll set. Ideally the daily CWSI should be compared with other more tedious methods of irrigation scheduling which are based on plant physiological measurements or estimates of available water. Use of the former is limited by large day-to-day and between plant variability; the latter is usually a point measurement handicapped by assumptions of plant root distribution and atmospheric evaporative demand. A second problem, perhaps not as critical from an operational standpoint, is whether the relationship between CWSI and photosynthesis is linear. Put another way, is a crop exhibiting a CWSI of 0.4 units for 2 days, as stressed as one showing 0.8 units for only one day?

The utility of a CWSI concept requires that systematic errors in the collection of data due to calibration uncertainty and/or experimental technique be kept to a minimum. Random errors are more tolerable since they tend to cancel out over a period of time. One way to minimize the effect of random errors for irrigation scheduling purposes is to calculate a running average or, alternatively, to accumulate CWSI with time resetting it to zero at each irrigation event. Then when the accumulation reaches a certain level it signals that irrigation is required. This is the approach we took in Figure 10, where all positive values of CWSI are summed from one irrigation to the next and that value is shown above each of the peaks. Linear interpolation is used in Figure 10 to account for missing weekend data.

The irrigations in the Cotton 80 experiment were scheduled on a calendar basis. Variable weather or crop stress measurements had no bearing on the amount or timing. As a result the maximum accumulated CWSI values attained during each irrigation cycle were variable also, and may reflect the actual water status of the crop. Based solely on Σ CWSI it appears that the sixth and possibly even the fourth irrigation of plot B2 were too early. On the other hand the second irrigation of Plot F2 was clearly delayed past an optimum point and was not sufficient to effect complete recovery. The third and fourth irrigation achieved recovery, but the CWSI sum was slightly higher than the average value of 2.4 ± 1.35 units we observed in cotton irrigated at 2-week intervals from mid June to mid August. Until CWSI data are interpreted in the context of independent measure of physiological status or growth rate a value of 2.4 might be a reasonable first approximation for irrigation scheduling.

Relative minor but systematic errors in the determination of air temperature, crop temperature or the crop baseline will be magnified considerably when the CWSI is accumulated with time. An example will serve to illustrate this point. Suppose a +1°C error is introduced into the measurement of air temperature due to an unshielded thermocouple. At an ambient temperature of 35° and a VPD of 40 mb, this will cause about 15% error per day. When accumulated over a 14-day interval this translates into 2.1 units of CWSI (90% of the response required to initiate an irrigation). Using an inappropriately derived baseline will also result in errors of that magnitude. Future work will be directed towards refinement of techniques and development of methodologies which eliminate systematic errors or at least minimize their contribution to the CWSI. Under consideration for example is an approach that would permit measurement of air temperature with the IR-thermometer. This would minimize the effect that instrument calibration error has on the plant and air temperature differential.

A CWSI was also calculated according to the energy balance approach proposed by Jackson et al (1981). Like the Idso CWSI it compensates for changes in air vapor pressure deficit and thus is considerably more powerful management tool than the conventional SDD. The Jackson CWSI additionally compensates for cloudy weather by taking levels of net radiation into account. Under cloudy conditions the Idso CWSI indicates a lower level of stress than might otherwise be expected.

In order to derive the Jackson CWSI from Cotton 80 data a number of assumptions were made to simplify the calculations. As a first approximation the aerodynamic resistance of the canopy was estimated to be 10 s m^{-1} and the canopy diffusion resistance of a well-watered crop set equal to 5 s m^{-1}. This is obviously a simplification of variables which change dynamically with canopy development and plant maturity but, as will be shown later is probably an adequate representation of a season-long average. Because instantaneous values of net radiation were not available for each plot a two step net radiation algorithm based on cloud cover was employed. Net radiation was assumed to be 600 W m^{-2} on days when the sun was unobstructed by clouds or covered by a thin layer of cirrus. On completely overcast days and whenever alternate sun/shade conditions persisted due to rapidly moving cumulus clouds, net radiation was set equal to 300 W m^{-2}.

The relationship between the Idso and Jackson CWSI for the entire Cotton 80 experiment (12 subplots x 83 days) is illustrated in Figure 11. These data show the range over which each index can be expected to vary due to crop stress conditions. The Idso CWSI varies from a low of -0.5 units to a maximum of +1.6 units, while the majority of the Jackson CWSI points lie within the 0 → 1 unit span which is predicted from energy balance considerations. This implies that the initial assumption for r_a and r_c was a reasonable estimate. There is a good linear relation between the two methods of calculating a CWSI for days when the direct beam solar is either unobstructed or partially obscured by thin cirrus, and on clear days both indices probably contain the same information regarding crop stress. On intermittent cloudy or completely overcast days though, differences in the two indices exist. If indeed, the Jackson CWSI more accurately reflects crop water status under low net radiation conditions then the Idso CWSI appears to underpredict crop stress by about 0.2 units. Additional work is needed to define which of these indices are more appropriate to use under cloudy conditions.

23. IR Thermometry in the Detection of Western Corn Rootworm Infestations

Thermal remote sensing techniques should prove applicable in the detection of any plant stress, either biological or physical which interferes in the transfer of water through the soil-plant-atmosphere continuum. We have observed, for example, that drought-stressed crops are often 8-10°C warmer than plants with an ample supply of water; leaves on cotton and sugarbeet plants infected with certain root rotting soil fungi are 3-5°C warmer than those on adjacent healthy individuals. Along these same lines, we reasoned that IR thermometry should prove useful in the timely detection of root pruning activities of soil insects. Accordingly an experiment to test this hypothesis was planned in conjunction with personnel at the Northern Grain Insects Research Laboratory, AR, SEA, USDA, at Brookings, South Dakota (Dr. Gerald R. Sutter, Location Leader).

The primary mission of scientists at that location is to conduct biological research on the interrelationship of grain insects and their hosts and to provide new and improved methods of pest control and management. Much of their research effort is directed towards understanding the ecology of the western corn rootworm (WCR), Diabrotica virgifera LeConte, an important economic pest of corn in the Midwest and Plains states. They have developed a procedure for artificially infesting large scale field plots with eggs of field-collected WCR beetles. This technique ensures a quantitative and uniform infestation of an insect pest which because of its uneven and erratic distribution is difficult to study in a natural field situation.

An ongoing field experiment designed to examine the effects of plant density on WCR survival appeared well-suited to test thermal IR detection techniques. The experimental approach consisted of a 14 May 80 planting of corn (Pioneer 3978) at four different densities (within row plant spacings of 15, 30, 45 and 60 cm). The soil was also innoculated at planting with WCR eggs at five rates (0, 300, 600, 900, and 1200 eggs/30 cm of row). This established 20 treatment combinations which were replicated four times. Each treatment consisted of a single EW row of corn ca 15 m in length that was separated from adjacent treatments by a single buffer row of a different variety of corn (Sokota TS49MF) planted at 30 cm intervals. Row spacing was 1 m.

Ground-based thermal IR measurements were taken on 8-10 July 1980 using a Telatemp AG-42 infrared thermometer (10.5-12.5 μm bandpass filter, 4° F.O.V.). At that time plants were ca 120-150 cm in height, row closure was not complete, and tasseling was about to begin. Although surface soil conditions were dry, sufficient soil moisture remained from a 12.5 cm rainfall (2 weeks prior) that no plants were wilting from moisture stress. The plant density experiment was chosen for intensive measurements because plants with the closest spacing were expected to develop limiting soil moisture conditions earliest. This, we felt, would exaggerate any temperature effect that WCR populations would have on corn plants.

The data collection routine consisted of 5-8 measurements of sunlit leaves near the top of the canopy for all treatments. Psychrometric measurements were made at a height of 150 cm within the field boundaries.

On 9 July, sky conditions were acceptable for taking measurements but a defective charger on the IR thermometer prevented data collection in the plant density experiment until mid-afternoon. Limited sets of data were collected for each planting density at treatments of 0 and 1200 eggs/30 cm row. The dry bulb temperature averaged 30.5°C during this time; the vapor pressure deficit was ca 23 mb. For each data set, treatments innoculated with 1200 eggs/30 cm averaged ca 0.5°C warmer than the controls. This temperature differential was not sufficient to discriminate between healthy and infested plants since natural variability among the plants, variability due to viewing geometry, occasional gust of winds and other factors could result in this much temperature difference.

On 10 July the observations were expanded to include two repetitions, four planting rates and five levels of infestation. Results for data collected between 1640 h and 1740 h (CDT) the only time period of 3 during which cirrus interference with the direct beam irradiance was minimal are shown in Table 7. When leaf temperatures were grouped according to either infestation levels or plant spacing the means were not statistically different. This implies that no differential soil moisture conditions had occurred as a result of the different plant densities. It is possible that the buffer rows which were each planted at the same 30 cm spacing were buffering the treatments to the extent that differences in soil moisture had not yet developed. It is also evident that plant temperatures do not appear to reflect WCR egg infestation levels. This was unexpected since many of the plants in infested rows were "loose" in the ground and required minimal effort to pull from the soil. The only plants which showed a 3-5°C increase in temperature over healthy plants were those which were severely "goosenecked" and showed visible wilting symptoms.

We believe that a combination of high soil moisture levels and compensatory changes in corn plant water relations obscured any effects of WCR on plant transpiration and temperature. Furthermore the timing of our investigation may have affected the results since the plants were beginning to develop a secondary root network following earlier damage by WCR. Perhaps with more limiting soil moisture conditions and damage inflicted at a point in crop phenology when compensation would not be likely, a temperature difference would be evident.

24. Measurement of Dew on Wheat Canopies

An experiment was designed to quantify the relationship between the amount of dew present on a wheat canopy and the observed depression of a spectrally derived vegetation index [i.e., the ratio of MSS 7 to MSS 5 wavebands; (0.8 to 1.1 μm)/(0.6 to 0.7 μm]. Plots representing five different planting dates of Produra wheat were selected from the Serial Cereal II experiment. Each was at a different stage of growth and had varying amounts of green biomass. On 19 March 1980 two target areas with canopies which appeared visibly very similar were designed within each plot: on the first, dew was expected to form the following morning, the second was to remain dewless as a consequence of 2 x 2 m, opaque "dew-out" shelters positioned about 50 cm above the canopy top and altering the down-welling thermal radiation regime during the night.

The shelters were removed shortly after dawn on 20 March and spectral measurements using an Exotech Model 100-A hand-held radiometer were made over both targets in each plot beginning at 0700 h and repeated at 13 intervals during the day. At 0630 and at hourly intervals thereafter, estimates of the amount of natural dew on a representative sample from each plot were derived by harvesting the above ground vegetation, gently transferring it to a tared plastic bag and weighing it. Then regardless of the amount of dew present, each sample was blotted dry for the same amount of time (7 minutes) and reweighed. Since the leaf area index for each canopy was known, it was possible to calculate the ground area subtended by the sample by measuring its leaf area. Then the dew per square meter data was converted to dew density by dividing by the height of the leaf portion of the canopy. A tissue water loss factor (i.e., the "dew density" observed during the 7-minute processing of a sample without dew) was subtracted from each value.

The natural dew density is shown for each of the plots in Figure 12. Curves through the data points were drawn by eye. The data show that dew accumulation was greatest on the plot with the highest green leaf area index (4B), and tapered off gradually with advancing phenological age and decreasing green leaf area. Plot 5B is an apparent exception. However, its canopy height was about one-third that of the other plots and increased dew density may be a result of different micrometeorological conditions. The increase in dew density at 0730 h in plots 4B and 5B was confirmed visually and on photographs. Dew dissipation followed time trends that are typical of late winter in Arizona with most noticeable dew disappearing shortly after 0900 h.

Spectral data for the control (3B East with dew out shelter) and treatment areas (3B West, natural dew in the morning), are shown in Figure 13. Note that the scale for the west subplot has been shifted upwards ca 1.50 units, an alignment required to normalize the subplots for slight differences in green biomass. The lines represent 2-point moving averages through the data and the trends shown for 3B are representative of those observed in other plots. The area having natural dew formation in the morning (3B West) exhibits a lower IR/red ratio than the control. In the afternoon an artificial dew condition was created in 3B east by misting the canopy with water 5-10 minutes prior to each set of readings. This caused a similar depression in the ratio. In both the natural and artificial dew cases, the change induced in the IR/red ratio is caused primarily by an increase in red radiance caused by the specular reflection from tiny dew droplets. When the data for each subplot were aligned and the graphic separation [i.e., the difference between the upper (dew absent) and lower (dew present) lines of Figure 13] calculated for each time period, a pattern emerged that was related to natural dew density. Figure 14 shows this relationship is linear and appears independent of green leaf area and phenological stage of development. A heavy dew density (0.4 kg m^{-3}) depressed the IR/red ratio by 3 regardless of its original value. By approximately 0930 h the visible dew had almost disappeared from the canopies, and the IR/red ratio had essentially returned to control levels.

Thus it appears feasible to use remote spectral measurements to detect and quantify the formation and dissipation of dew. Dew assessment may also play a role in the prediction of dew-related plant diseases. In addition, the effects of dew on spectral vegetation indices merit serious consideration when timing aircraft or satellite data acquisitions over agricultural areas where dew phenomena occur. Failure to take dew into account could lead to serious errors in the estimation of agronomic parameters from spectral data.

SUMMARY AND CONCLUSIONS:

A crop water stress index was developed from the stress degree day concept to quantify plant stress. The index can be empirically derived by accounting for both air temperature and the vapor pressure deficit of the atmosphere. Additionally from energy balance considerations, theoretical upper and lower bounds of the canopy-air temperature differential (as a function of vapor pressure deficit) can be derived. The upper bound is for a dry, non-transpiring crop, and the lower bound is for a well-watered crop evaporating at potential. The crop water stress index, from the empirical technique and theoretical method, is merely the distance of the data point (canopy-air temperature differential at a given vapor pressure deficit) from the lower bound divided by the total distance between the upper and lower bounds.

The crop water stress index was evaluated using an independent plant measurement of stress for comparison. It was shown that the index is uniquely related to the total plant water potential of alfalfa grown in two widely separated environments — Arizona and Minnesota. A similar relationship was developed for wheat growing in Arizona.

In a similar vein, experiments demonstrated that the equivalence point of plant and air temperatures is not a universal constant in the vicinity of 33°C, as has long been tacitly assumed to be the case for well-watered vegetation. Instead, it is shown that the equivalence point is a dynamic variable, responding to both plant and environmental factors.

A small, portable radiometer was used to identify a nutrient deficiency in sugarcane under variable sunlight conditions. The ratio of reflected near infrared to visible red light as measured with the radiometer clearly indicated deficiencies of nitrogen but not potassium.

A set of notes was developed to aid the beginner in hand-held radiometry. The electromagnetic spectrum is reviewed, and pertinent terms are defined. View areas of multi-band radiometers are developed to show the areas of coincidence of adjacent bands. The amounts of plant cover seen by radiometers having different fields of view are described. Vegetation indices are derived and discussed. Response functions of several radiometers are shown and applied to spectrometer data taken over 12 wheat plots, to provide a comparison of instruments and bands within and among instruments. The calculation of solar time is reviewed and applied to the calculation of the local time of LANDSAT satellite overpasses for any particular location in the northern hemisphere. The use and misuse of hand-held infrared thermometers are discussed, and a procedure for photographic determination of plant cover is described.

An experiment on cotton was conducted in the south San Joaquin Valley of California entirely by a farmer during the summer of 1980 to determine if foliage temperatures could be used to schedule irrigations. He also measured petiole water content frequently as he determined from previous research that this parameter could be used for irrigation scheduling. The data were collected by the farmer and processed by us. The crop water stress index follows, in an opposite fashion, the petiole water content as a function of time. As the plant dehydrates, due to lack of soil moisture, the PWC decreases and the CWSI increases. Because of the limited data set over several irrigations the whole season picture is incomplete. However, the trend is clear: the CWSI is reasonably well correlated with PWC (r^2 = 0.53). Also, the results show that both the average petiole water content (PWC), and average crop water stress index (CWSI) are good predictors of cotton lint yield. Additional research will be conducted in 1981 at Westlake Farms and at Phoenix to verify the CWSI-PWC relationship and to investigate how the CWSI can be used to schedule irrigations for cotton.

A lysimeter Evapotranspiration Micrometeorological Experiment (LETME) was conducted during June and July 1980 at 11 research locations in the United States. The purpose of this project was to evaluate the stress-degree-day concept and the crop water stress index on different crops under different climatic regimes. Since nine of the eleven locations had precision weighing lysimeters, data were collected to evaluate several evapotranspiration models for comparison against lysimetric data. In addition, various shortwave and longwave radiation models were to be evaluated under the various climatic regimes. The locations varied in latitude from 26°N to 46°N, in longitude from 93°W to 121°W, and in elevation from -30 m to 3337 m, a wide range of conditions. Weather conditions were quite good and there was at least one completely clear day at each location.

The trip was accomplished using a mobile van from the University of California, Davis, which housed all the necessary equipment and computer-based data acquisition system. Drs. Jerry Hatfield (UCD), Sherwood Idso (USWCL) and Robert Reginato (USWCL) were the data gatherers on the trip. All instruments were calibrated prior to and immediately following the 9-week trip. A unique feature of the trip was that all data were collected in a nearly identical manner at all locations and the instruments and setups were identical at all locations.

All the manually obtained data have been entered in the computer so it can be processed in conjunction with the micrometeorological data. All of the data are currently being analyzed to meet the objectives of LETME.

The three automatic weighing lysimeters in our backyard were refurbished. They were completely excavated and new horizontal flexures were machined and installed as the old ones had buckled. The interiors of the three weighing mechanisms (coffins) were cleaned, new loadcells installed, and the complete system reassembled in place. Proper caulking and moisture seals were installed to prevent any moisture from entering into the coffins. The system was calibrated by adding known weights on the bin and noting the voltage output from the loadcell. The standard error of the estimate from the regression analysis of the calibration was 1.0000 for each of the lysimeters.

We obtained a comprehensive data base from 37 experimental Produra wheat plots that were planted on 10 different dates (October 1978 through February 1980) and irrigated at different times to provide several levels of crop water stress. Routine measurements included: (1) twice weekly estimates of plant growth stage, leaf area index, biomass, etc.; (2) grain yield components; (3) 20-minute observations of meteorological parameters; (4) soil water content estimated 3 days per week with a neutron scattering technique; (5) daily radiant crop canopy temperatures at 1340 h (MST); and (6) crop canopy radiance in two visible and two near-IR reflective wavebands. These data will enable a comparison of reflective and thermal remote sensing approaches to the detection of water stress in wheat canopies which differ in phenology and biomass levels.

We observed final yields which varied from less than 25 g/m^{-2} for plots that were planted in May to more than 500 g/m^{-2} for plots planted during the optimum fall planting window. Yields were depressed whenever crops were subjected to moisture stress or encountered unusually low or high temperatures during critical periods of development (especially anthesis and grain ripening).

Results from a season-long cotton experiment at Phoenix demonstrated that two crop water stress indices (CWSI) derived from radiant leaf and canopy temperatures and wet and dry bulb temperatures are related to crop water stress as inferred from days since the last irrigation. The CWSI drops to a minimum following an irrigation, then climbs steadily as stress develops prior to the next water application. A comparison of leaf (T_ℓ) and Canopy (T_c) temperatures showed that a 10-15°C discrepancy may exist between T_ℓ and T_c early in the season due to the influence of hot dry soil on the latter temperature. Prior to the time when 90% of an infrared thermometer's field of view is plant material, actual leaf temperatures should be used for inferring plant water stress.

Results of a preliminary study to investigate the utility of IR thermometry in the early detection of western corn rootworm infestations at Brookings, South Dakota, were non-conclusive. The root pruning activities of this insect was expected to impede the plant's ability to extract water from the soil, thus limiting transpiration and causing an increase in plant leaf temperature. Our results showed that corn growing in soils which had been infested with corn rootworm eggs at rates of 300, 600, 900, and 1200 eggs/30 cm had leaf temperatures which did not differ from the controls. The investigation, however, was conducted over a several day period just prior to tasseling. The root pruning activity of the larvae may have passed it peak and the plants were beginning to compensate for earlier damage by developing a secondary root network. In addition, because soil moisture conditions were relatively high, plants with a limited root network may have been able to extract sufficient water to meet environmental demand. A longer term investigation with different levels of soil moisture will probably be required to determine if IR thermometry has any value in the early detection of rootworm infestations.

A study was conducted at Phoenix, Arizona to document the difference in spectral radiance from a wheat canopy with natural dew formation and an adjacent portion of that canopy on which the formation of dew was minimized by a removable opaque shelter. We observed that dew decreased the IR/Red vegetation index by increasing the specular reflection of red light from tiny water droplets on leaf surfaces. The amount by which the vegetation index is decreased is linearly related to the density of dew on the canopy. It is not dependent upon the green leaf area or stage of growth. Thus, a multitemporal sequence of spectral measurements can be used to quantify the formation and dissipation of dew for disease prediction and energy balance studies. The effects of dew should also be considered when timing data acquisition in dew prone areas. Failure to take dew effects into account could lead to misidentification of agricultural targets or erroneous interpretation of a crop's agronomic parameters.

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TABLE 1. Westlake Farms irrigation schedule for Acala cotton experimental plots.

Plot #	TRT	Preplant Jan 80	1 24 Jun 80	2	3	4	5
1	Wet	√	√	15 Jul	30 Jul	12 Aug	01 Sep
2	Dry	√	√	22 Jul	08 Aug	–	–
3	Med	√	√	19 Jul	04 Aug	19 Aug	–
4	Dry	√	√	22 Jul	08 Aug	–	–
5	Med	√	√	19 Jul	04 Aug	19 Aug	–
6	Dry	√	√	22 Jul	08 Aug	–	–
7	Wet	√	√	15 Jul	30 Jul	12 Aug	01 Sep
8	Wet	√	√	15 Jul	30 Jul	12 Aug	01 Sep
9	Med	√	√	19 Jul	04 Aug	19 Aug	–

TABLE 2. LETME locations and crops

LOCATION		LATITUDE	LONGITUDE	ELEVATION (m)	LYSIMETER CROP	OTHER CROPS
Brawley	CA	32°57'N	115°33'W	-30	Cotton	Bare Soil
Weslaco	TX	26°13'N	97°59'W	20	Bare Soil	None
Temple	TX	31°03'N	97°21'W	152	Sorghum	Corn
Manhattan	KS	39°09'N	94°40'W	320	Sorghum, Millet	Sugarbeets
Lincoln	NE	41°09'N	96°36'W	354	Soybeans	Alfalfa, Sunflower, Bromegrass
Madison	WI	44°07'W	89°32'W	328	Not Functioning	None
St. Paul	MN	44°59'N	93°11'W	295	Alfalfa	Wheat, Barley, Flax, Soybeans, Oats, Bare Soil
Fargo	ND	46°54'N	96°48'W	273	Soybeans	Alfalfa Bare Soil
Sidney	MT	47°46'N	104°16'W	689	Dead Wheat	Sugarbeets, Alfalfa, Spring Wheat
Beartooth Pass	WY	44°58'N	109°28'W	3337	None	Alpine Meadow
Twin Falls	ID	42°34.5'N	114°25'W	1198	Alfalfa	Beans
Davis	CA	38°32'N	121°45.5'W	18	Tomato	Bare Soil

TABLE 3. LETME Sensors and Frequency of Measurements

SENSOR	LOCATION	FREQUENCY OF MEASUREMENT
Recorded by computer		
Direct Normal Incidence Pyronometer with 4 filters	Top of Van (3 m)	1 minute continuously
Global pyronometer	" "	"
Diffuse pyronometer	" "	"
Ultraviolet radiometer	" "	"
Total radiation, Swissleco	" "	"
Air temperature	" (6 m)	"
Dew point	" "	"
Wind speed	" "	"
Wind direction	" "	"
Dry bulb temperature	30,130 cm above lysimeter crop	"
Wet bulb temperature	"	"
Wind speed	"	"
Net radiation	"	"
Reflected solar radiation	"	"
Manually recorded		
Canopy temperature with infrared thermometer	In lysimeters and other fields	Variable from 10-45 min sunrise to sunset
Dry bulb temperature	Near lysimeters and other fields	"
Barometric pressure	In van	"
Visual weather observations	Near lysimeters	"
Lysimeter weight	At lysimeter	"

TABLE 4. Lysimeter calibrations after repairs (26 January 1981) and installation in field

LOAD CELL OUTPUT (MV)

Weight on Bin (kg)	Lysimeter #1	Lysimeter #2	Lysimeter #3
0	33.762	40.476	34.342
12.5	35.862	32.644	26.370
25.0	17.863	24.771	18.365
37.5	9.947	16.863	10.259
50.0	1.966	9.071	2.214
55.0		5.885	
60.0		2.750	
55.0		5.876	
42.5		13.925	
37.5	9.993		10.258
30.0		21.563	
25.0	17.842		18.335
17.5		29.459	
12.5	25.864		26.397
5.0		37.324	
0	33.766	40.517	34.371
Slope (kg/mv)*	-1.57215	-1.59060	-1.55497
r^2	0.99999	0.99998	0.99999

* 1 kg water spread on the lysimeter (1 m^2) is equivalent to 1 mm water depth.

Table 5. Cultural operations, rainfall and irrigations

Plot	Planting Date: Calendar	Planting Date: Julian	Seeding Rate kg/ha	Preplant Fertilizer kg/ha: N	Preplant Fertilizer kg/ha: P	Rain (cm)	Irrigations: Preplant Date	Irrigations: Post Plant No.	Irrigations: Post Plant Amount (cm)
1A	31 Oct 78	78304	≈127	221	85	23.4	284	2	27.2
1B	"	"	"	"	"	"	"	1	15.2
1C	"	"	"	"	"	"	"	2	29.3
1D	"	"	"	"	"	"	"	4	42.2
2A	13 Dec 78	78347	≈127	230	88	17.4	"	1	18.6
2B	"	"	"	"	"	"	"	2	30.1
2C	"	"	"	"	"	"	"	3	41.2
2D	"	"	"	"	"	"	"	5	57.0
3A	13 Feb 79	79044	≈127	235	90	5.3	"	3	36.4
3B	"	"	"	"	"	"	"	5	55.1
3C	"	"	"	"	"	5.2	"	2	29.2
3D	"	"	"	"	"	"	"	1	15.9
4A	15 Mar 79	79074	≈127	216	83	5.1	"	3	28.7
4B	"	"	"	"	"	"	"	5	49.4
4C	"	"	"	"	"	"	"	3	30.7
4D	"	"	"	"	"	"	"	4	36.5
5A	1 May 79	79121	>127	257	99	2.4	"	7	58.0
5B	"	"	"	"	"	"	"	11	97.8
5C	"	"	"	"	"	"	"	8	71.7
5D	"	"	"	"	"	"	"	8	74.3
1A	28 Sep 79	79271	117	283	93	14.6	249	4	37.1
1B	"	"	107	282	"	"	"	5	53.0
1C	"	"	112	296	114	"	250	4	38.3
2A	22 Oct 79	79295	112	259	99	14.5	274	3	32.9
2B	"	"	103	262	101	"	263	3	31.6
2C	"	"	91	257	98	"	"	4	38.2
3A	14 Nov 79	79318	114	261	100	15.0	----	12	19.7
3B	15 Nov 79	79319	98	258	99	"	255	2	20.7
3C	"	"	"	265	102	"	----	2	19.3
4A	18 Dec 79	79352	123	238	92	14.2	313	1	9.9
4B	"	"	117	237	93	"	"	3	29.5
4C	"	"	122	243	94	"	317	2	22.2
4D	"	"	"	"	"	"	"	2	20.2
5A	6 Feb 80	80037	118	280	106	9.8	341	2	22.3
5B	"	"	"	286	110	"	"	5	50.0
5C	"	"	"	290	111	"	"	3	31.2
5D	"	"	"	281	108	"	"	3	32.9

Table 6. Agronomic Parameters

Plot	Planting Date	Plant Density Emerg.	Plant Density Harvest	Heads per Plant	Seeds per Head	1000 Seed Wt. (g)	Final Yield gm^{-2} Dry Wt. ±SD
1A	78304	108	---	3.8	32	42	551 ± 57.1
1B	"	114	---	3.8	27	27	326 ± 12.2
1C	"	111	---	4.0	27	31	377 ± 39.1
1D	"	115	---	4.0	24	49	531 ± 18.3
2A	78347	91	---	2.7	32	26	210 ± 13.7
2B	"	110	---	2.4	31	36	296 ± 24.8
2C	"	93	---	3.5	34	33	369 ± 18.8
2D	"	100	---	3.0	40	46	554 ± 4.1
3A	79044	74	---	2.9	25	32	170 ± 29.8
3B	"	84	---	3.7	30	36	329 ± 69.8
3C	"	76	---	2.3	20	24	84 ± 5.5
3D	"	86	---	1.7	19	26	71 ± 5.6
4A	79074	32	28	3.8	20	25	51 ± 3.7
4B	"	58	53	4.2	20	31	138 ± 18.1
4C	"	61	52	3.9	18	23	86 ± 4.1
4D	"	44	41	4.5	17	29	90 ± 5.4
5A	79121	85	8	1.5	4	25	1 ± 1.1
5B	"	92	54	1.5	4	25	9 ± 4.0
5C	"	68	47	1.7	4	25	9 ± 3.8
5D	"	71	48	2.4	7	28	22 ± 1.8
1A	79271	64	---	4.3	18	58	287 ± 54.5
1B	"	80	---	3.7	17	56	284 ± 30.7
1C	"	109	---	2.7	17	56	272 ± 86.7
2A	79295	117	117	2.7	32	48	492 ± 34.3
2B	"	109	115	3.7	30	43	540 ± 23.5
2C	"	113	117	3.0	30	42	431 ± 41.6
3A	79318	126	128	2.8	28	24	235 ± 29.9
3B	79319	147	142	2.8	33	31	417 ± 42.3
3C	"	131	126	2.9	26	23	226 ± 2.4
4A	79352	215	217	1.5	25	23	181 ± 2.7
4B	"	212	209	2.2	34	24	384 ± 28.0
4C	"	216	203	1.5	27	36	306 ± 23.0
4D	"	219	204	1.6	30	29	293 ± 13.7
5A	80037	231	222	1.4	24	24	187 ± 5.3
5B	"	224	229	1.4	30	45	430 ± 42.2
5C	"	214	218	1.4	17	42	215 ± 12.8
5D	"	216	215	1.4	27	36	308 ± 14.7

Table 7. The influence of different infestation levels of WCR and plant density on the radiant temperatures of corn leaves prior to tasseling. Data were collected from 1643-1740h (CDT) on 10 July 80; air temperature was 33.4°C, vapor pressure deficit was 25.5 mb.

Infestation eggs/30 cm	n	Average Temperature (°C)	S.E.
0	51	28.5	0.10
300	55	28.4	0.11
600	43	28.4	0.14
900	54	28.4	0.11
1200	45	28.3	0.10

Plant Spacing (cm)	n	Temperature (°C)	S.E.
15	59	28.3	0.10
30	67	28.3	0.07
45	66	28.5	0.12
60	56	28.4	0.09

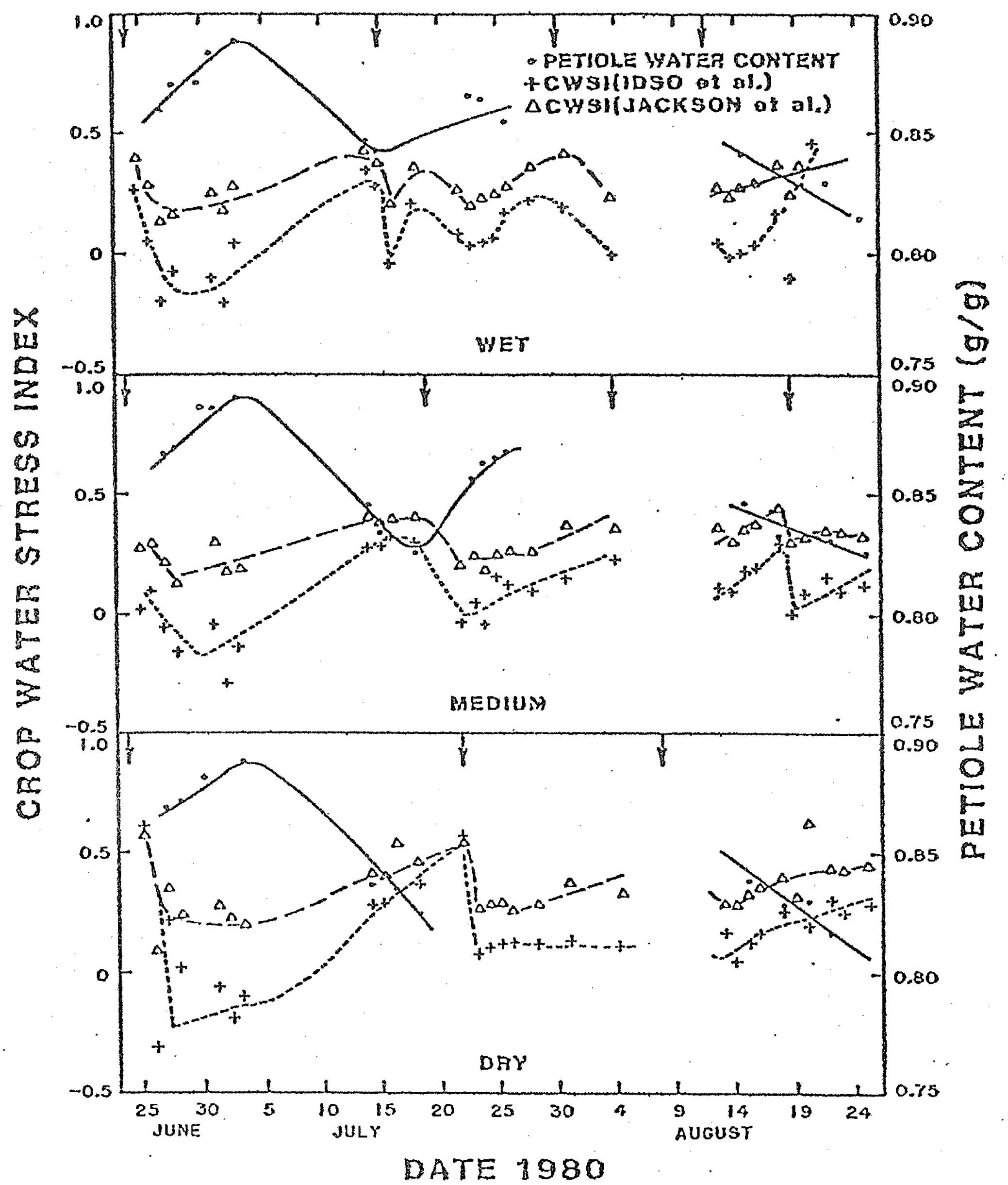


Fig. 1. Petiole water content and crop water stress index plotted as a function of time for three irrigation treatments.

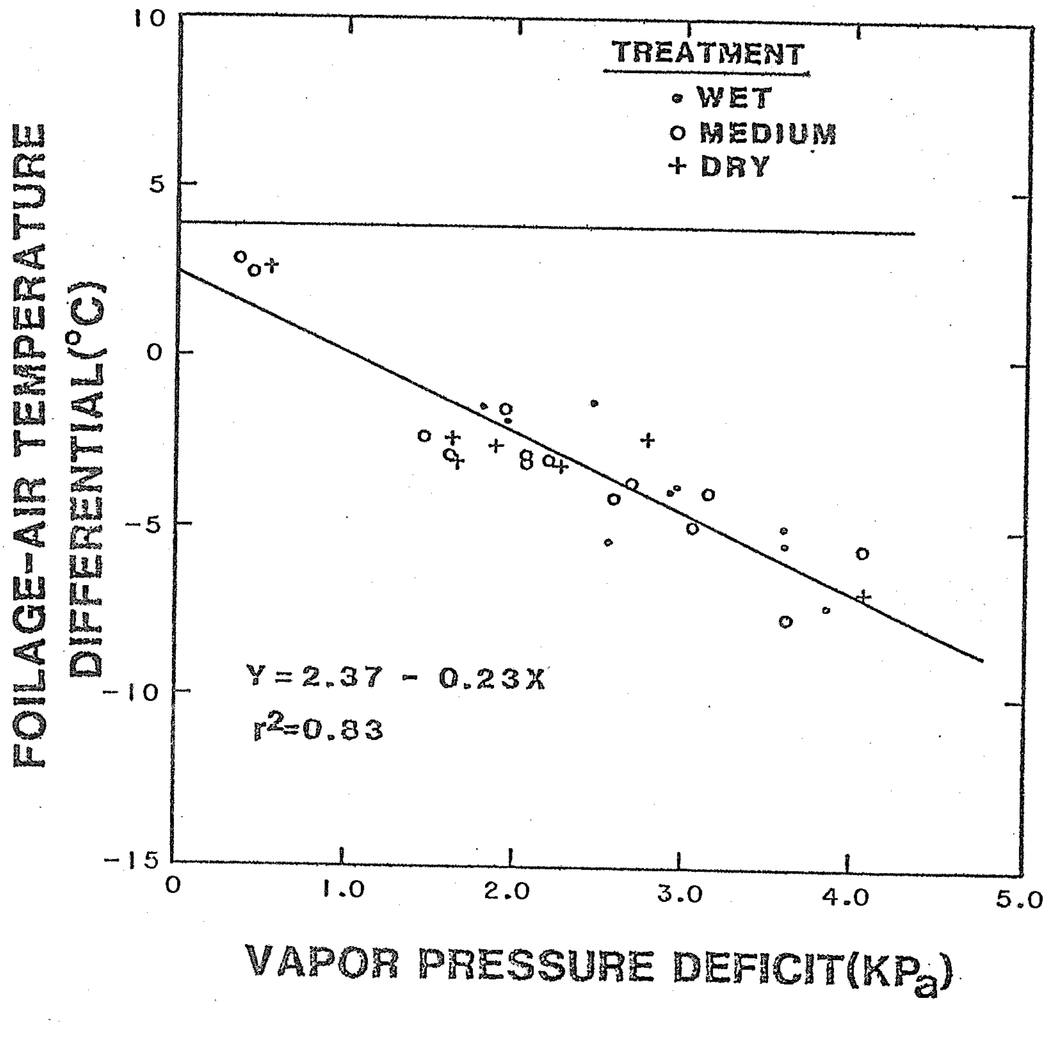


Fig. 2. Foliage-air temperature _vs_ vapor pressure deficit for well-watered cotton.

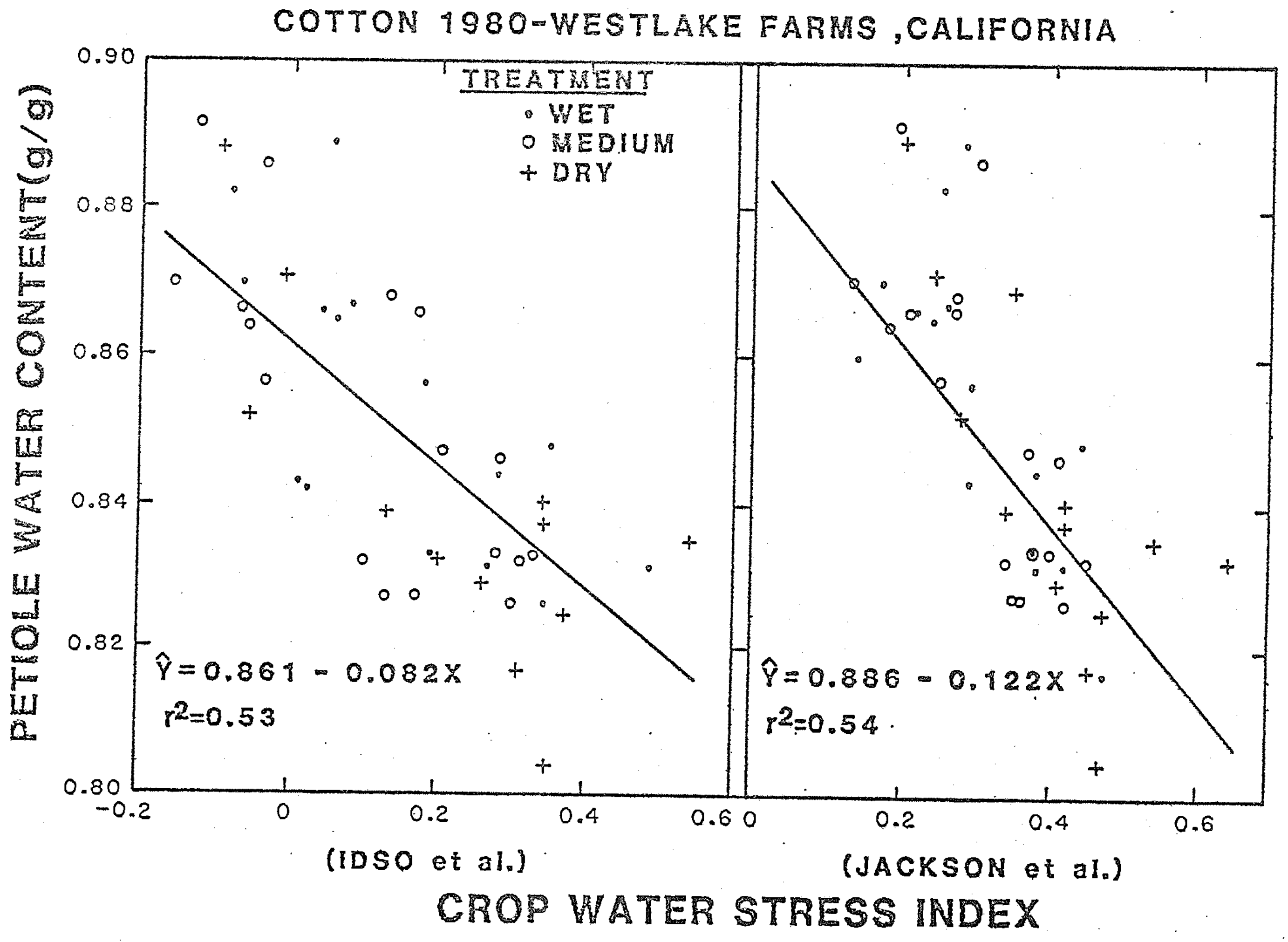


Fig. 3. Relationship between two crop water stress indices and petiole water content for cotton.

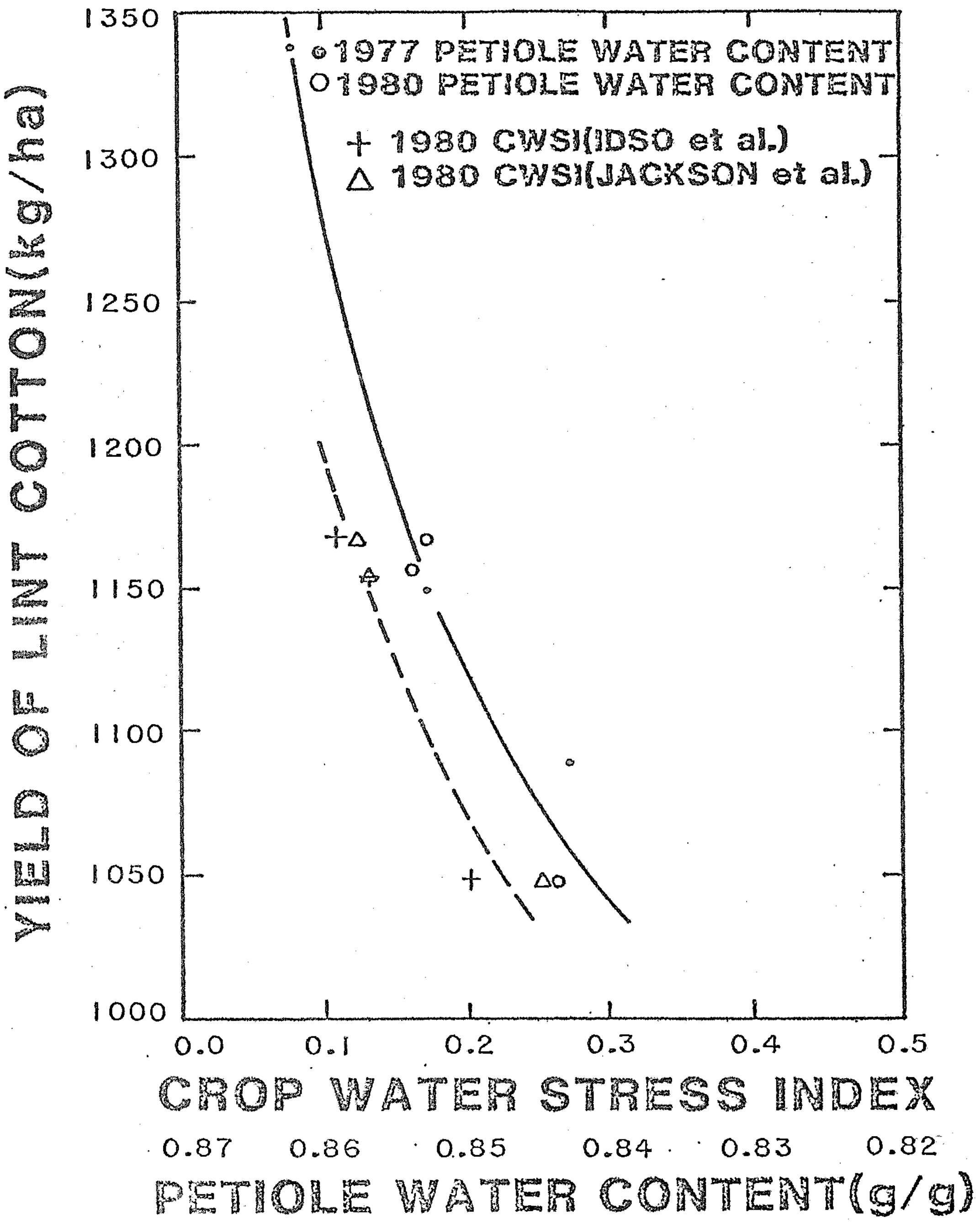
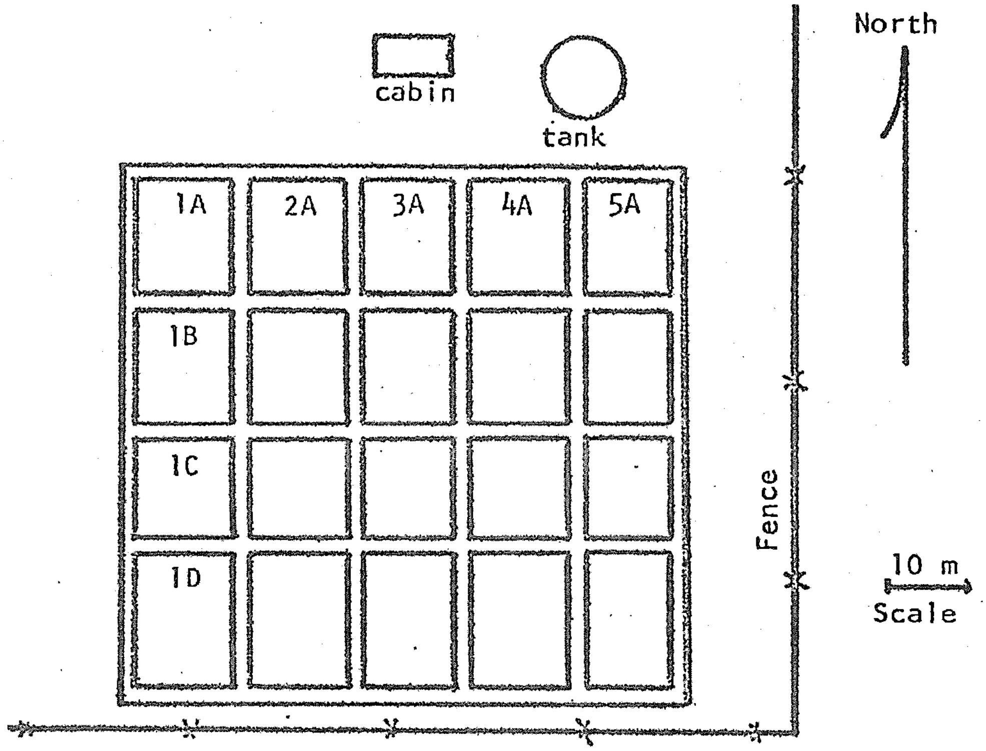


Fig. 4. Yield of lint cotton vs crop water stress index for 1980 growing season and vs petiole water content for 1977 and 1980 seasons.



FIELD LAYOUT

SERIAL CEREAL I - SUBPLOT SERIAL CEREAL II - SUBPLOT

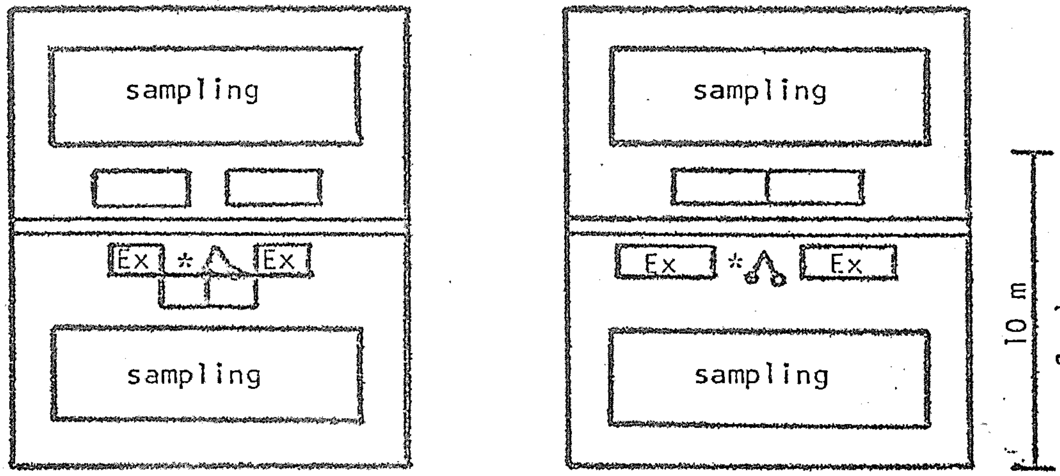
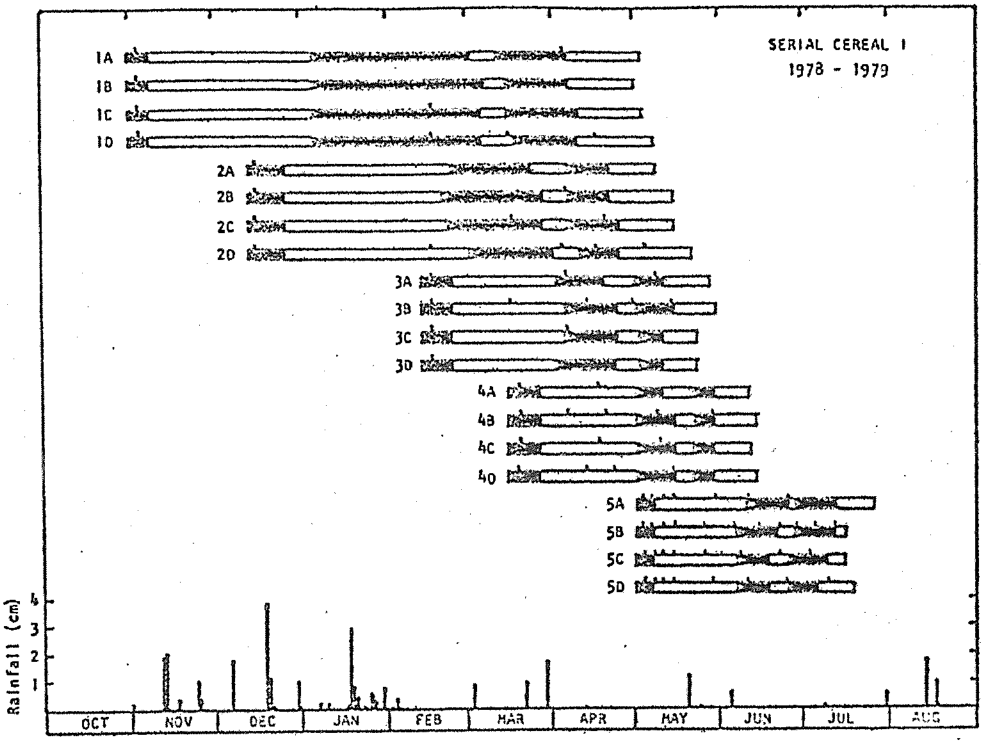


Fig. 5. Water Conservation Laboratory backyard field and plot layout for the 1979-1980 serial cereal wheat experiments.



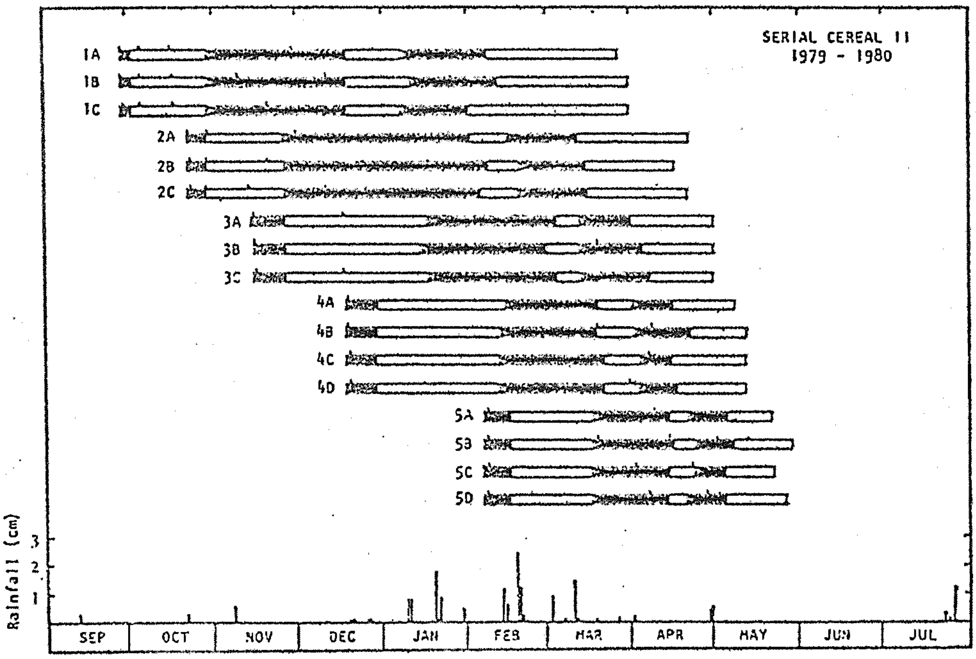


Fig. 6. The developmental duration of Produra wheat planted at ten different dates during Serial Cereal I & II experiments. The alternating horizontal segments of each bar represents the duration of successive phenological stages (see text). Tick marks above bars indicate irrigations. Rainfall is represented by vertical lines along the lower axis.

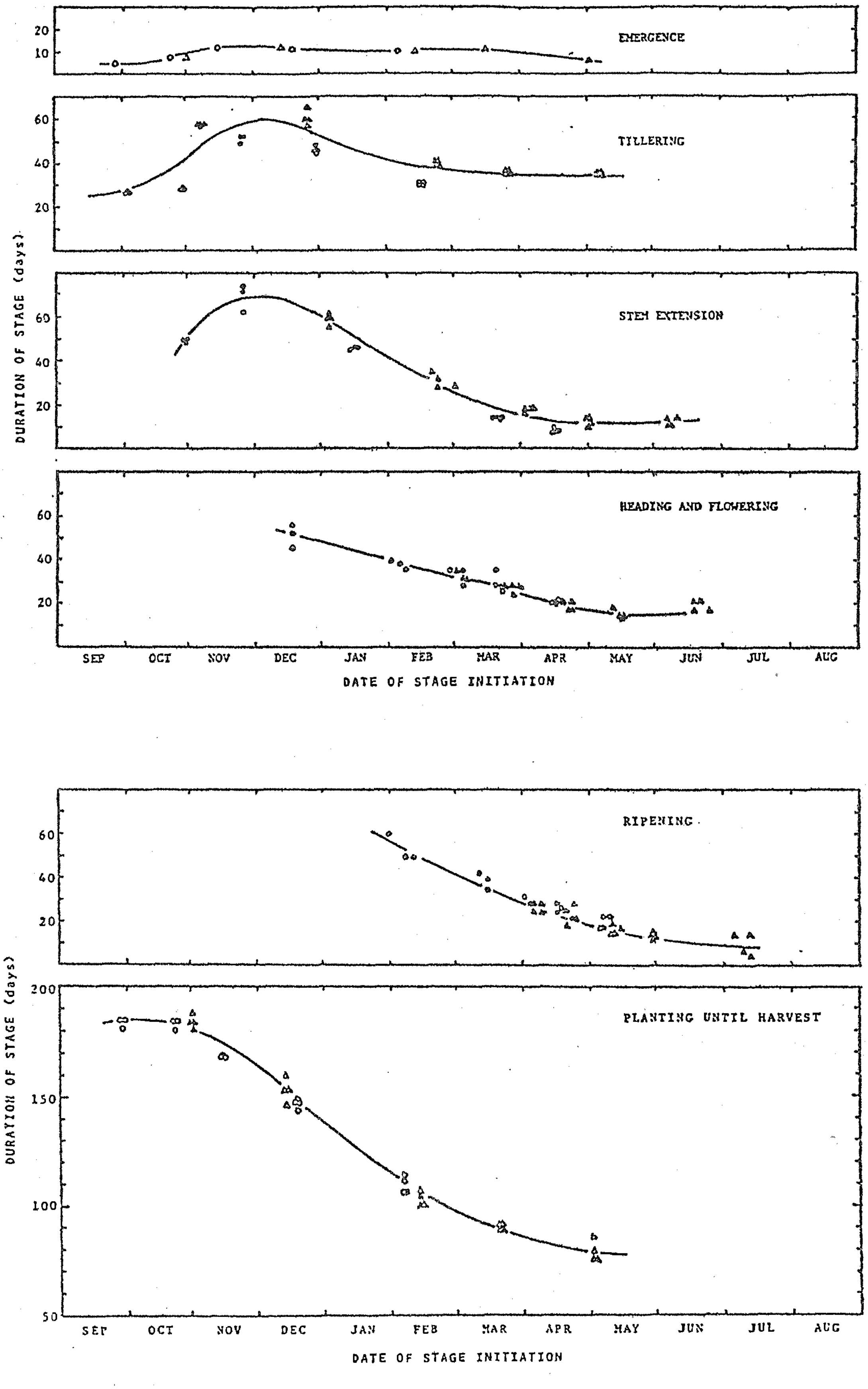


Fig. 7. The duration of major phenological stages versus the observed date of stage initiation. Symbols: Triangles - Serial Cereal I; circles - Serial Cereal II.

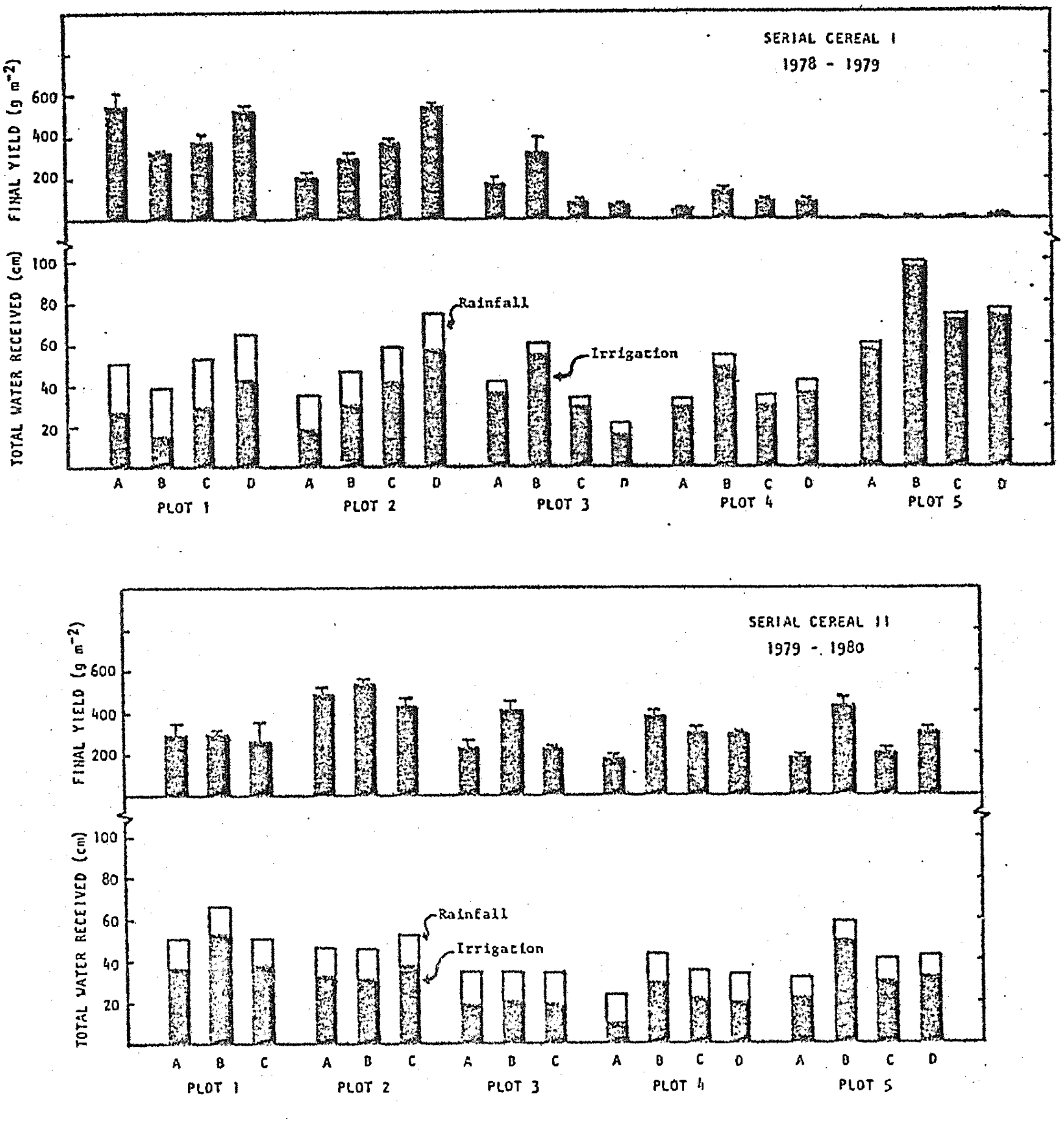
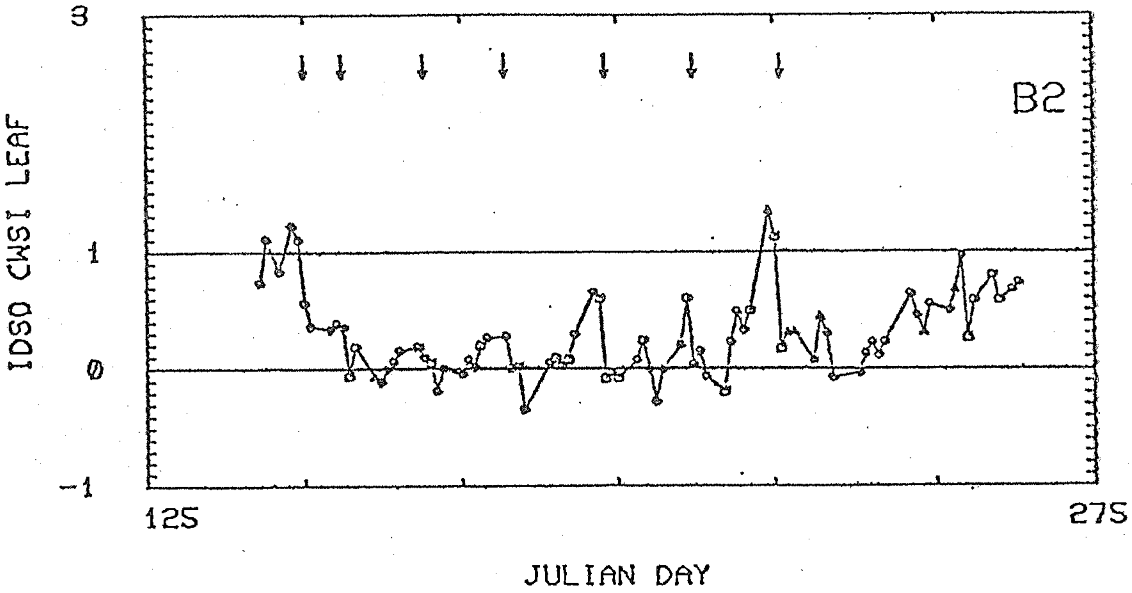


Fig. 8. Dry grain yield (+ 1 SD) and total water received by each plot in Serial Cereal I & II.



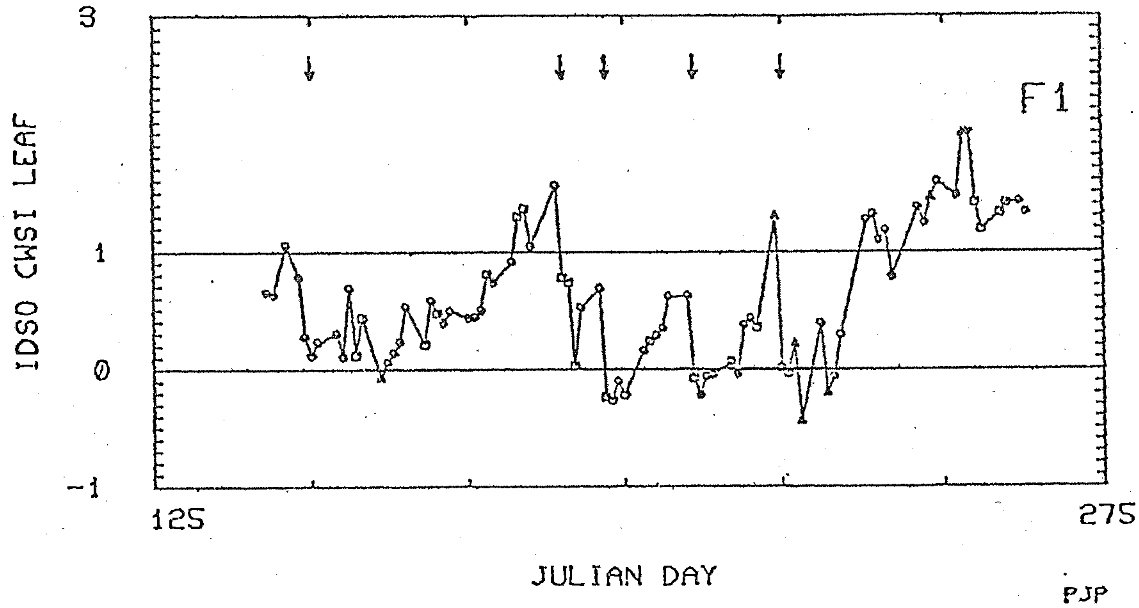


Fig. 9. Daily crop water stress index for two cotton irrigation treatments during 1980. Irrigations are represented by arrows along the upper axis.

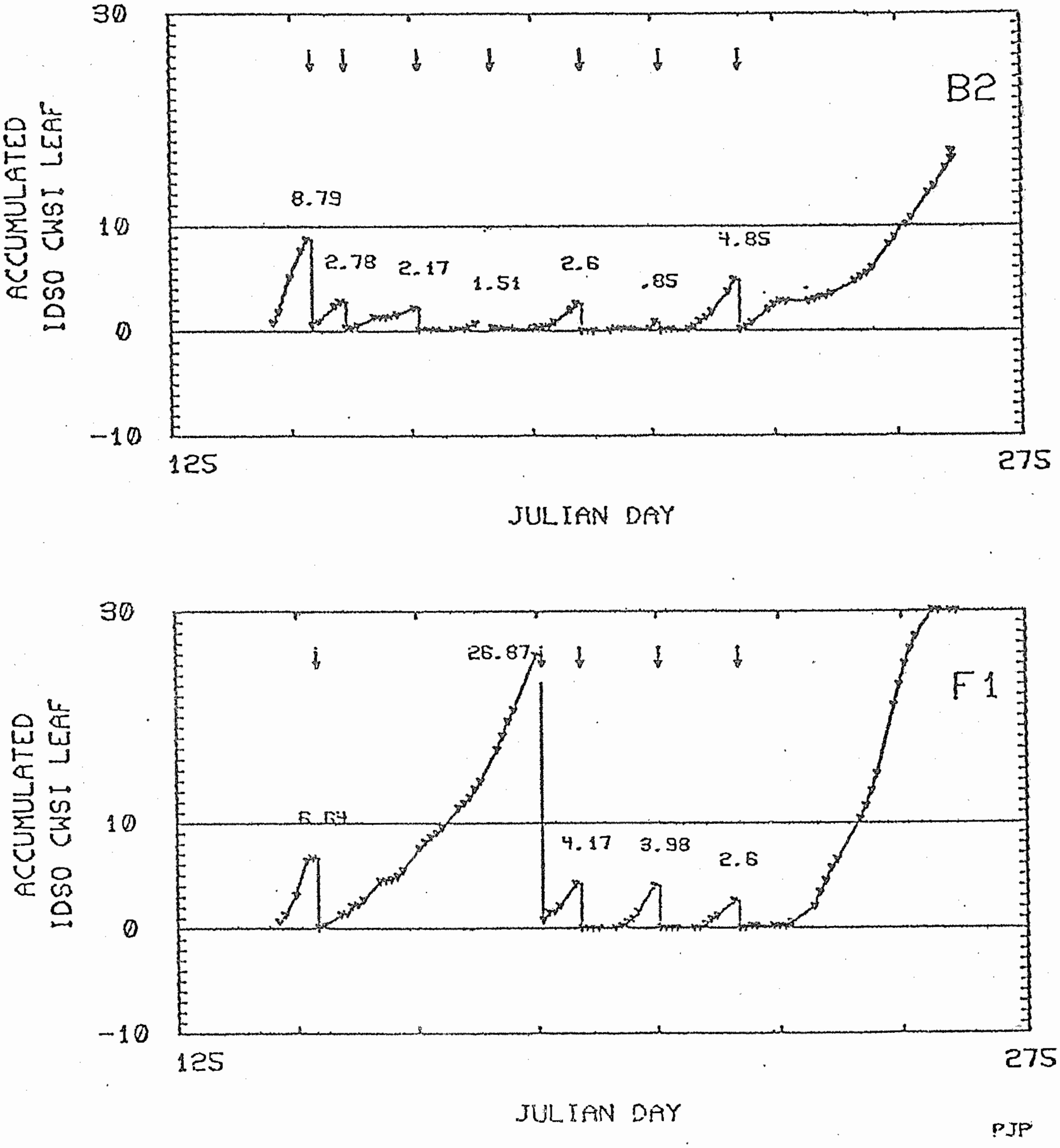


Fig. 10. Accumulated positive values of the crop water stress index for two irrigation treatments in 1980. Total accumulated at the time of irrigation are shown above each peak. Accumulations were reset to zero at each irrigation.

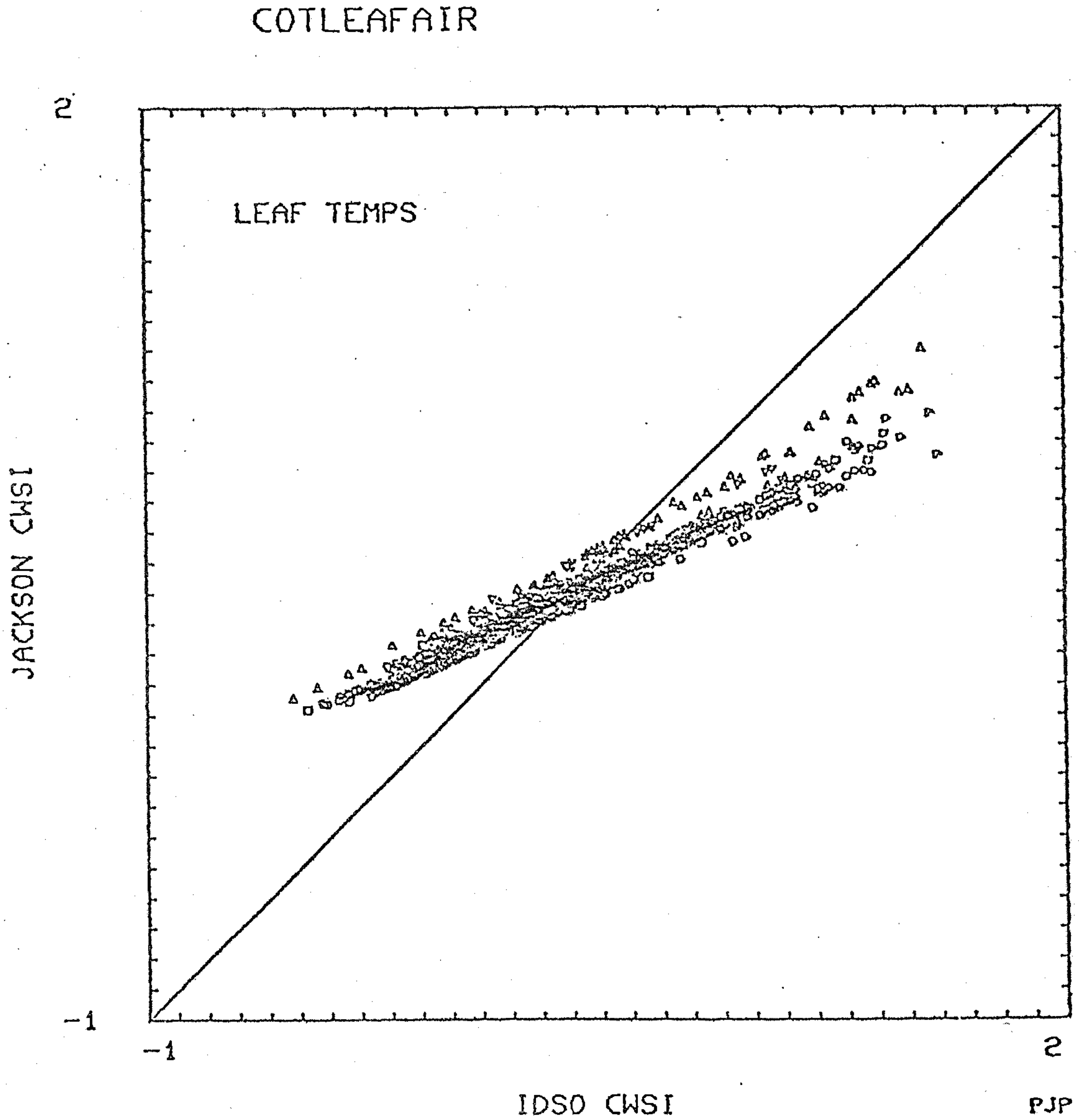


Fig. 11. The relation between the crop water stress index calculated by the theoretical approach of Jackson et al. and the empirical approach of Idso et al. Symbols represent condition of direct beam insolation (O - clear; - partial cirrus in direct beam; Δ - intermittent sun and shade from cumulus clouds; V - complete overcast).

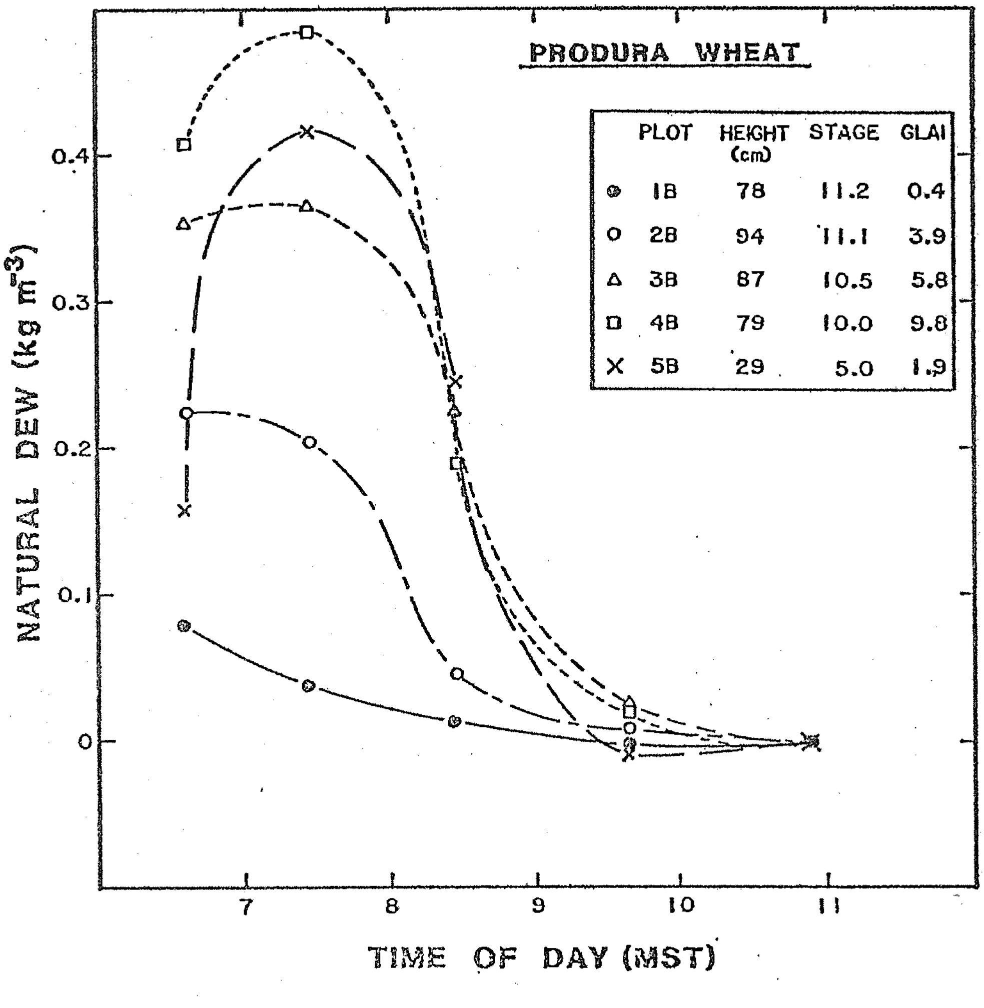


Fig. 12. The density of natural dew on unsheltered portion of each plot versus time. Inset documents canopy characteristics.

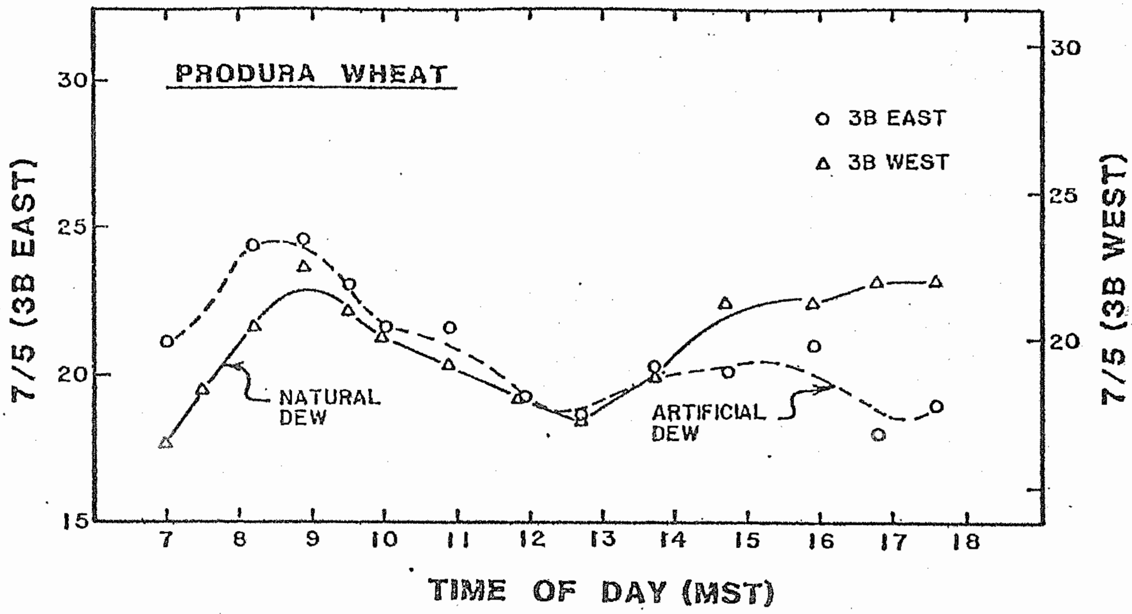


Fig. 13. The diurnal change in a spectrally-derived vegetation index (the ratio of Band 7 to Band 5) showing the effect of natural dew in the morning on 3B West and artifical dew in the afternoon in 3B East.

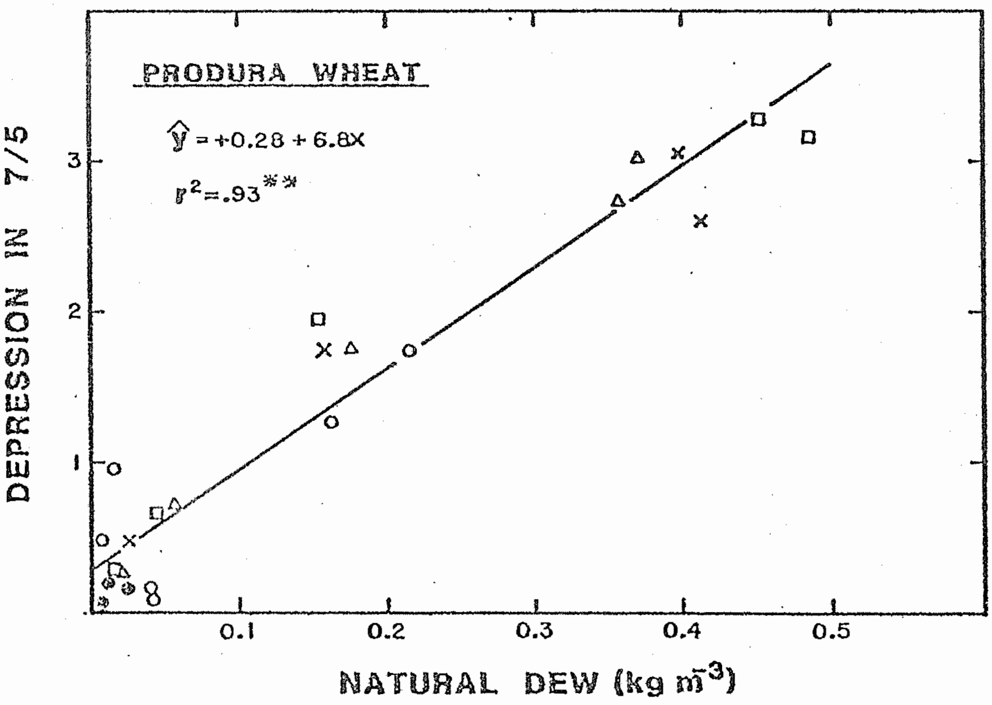


Fig. 14. The relation between dew density and the depression in the vegetation index.

TITLE: CARBON DIOXIDE ANALYSIS WITH A MODIFIED INFRARED GAS ABSORPTION TECHNIQUE

NRP: 20760 CRIS WORK UNIT: 5510-020760-004

INTRODUCTION:

The gas chromatographic method that has been used at this laboratory for CO_2 analysis based on thermocouple detection had a sensitivity of 25 ppm and was not adequate for the CO_2 soil flux and portable field photosynthesis chamber investigation. An order of magnitude increase in sensitivity with similar small-volume sample size capability was required. Thus, an infrared gas analyzer system was investigated to see whether suitable modification could be made to provide analytical accuracy meeting our research needs.

PROCEDURE:

The system described by Clegg, Sullivan and Eastin (1978) was used as a basis for developing our CO_2 analyzer. The dual column infrared gas analyzer (Beckman Model 315B) was modified to permit carrier gas to flow through one detector tube into another. The principle of operation is similar to that of the gas chromatograph, but the absorption column is not used. As shown in Figure 1, nitrogen gas was first passed through an ascarite absorber to remove any CO_2 contaminant in the N_2, a flowmeter (flow rate ≅ 0.9 liter/min), and a drying tube containing magnesium perchlorate and into one-half of the dual-tube infrared detector system. The gas then was directed through an electrically activated gas sampling valve (Carle, Model 4200 valve actuator) and injection port before continuing through the second infrared detector tube and out into the atmosphere. The port could be used for introducing samples with a gas syringe. The valve provided a way to inject highly reproducible gas volume. By attaching different loop sizes, the sample volume could be varied. The gas flow system was different from that of Clegg et al., in that we used a single stream through the two detectors, whereas they split the gas stream to get separate flows into the two detectors. The same carrier gas flow rate into the dual tubes was difficult to attain with the changes we made in our system, so that the alternate single flow system was used.

The output signal from the gas analyzer amplifier was taken on a chart recorder (Leeds & Northrup, Model "H," Azar) using the 0 to 10 mV range.

For calibration of the analyzer, different volumes (1 to 5 ml) of a standard CO_2 gas were injected into the system and the output recorded. Each incremental volume contained a proportional amount of CO_2.

RESULTS AND DISCUSSION:

The calibration curve derived from the standard reference gas is presented in Figure 2. The output was linearly related to the sample volume or in this case the concentration of CO_2. As illustrated in the figure, the sensitivity of the analyzer amplifier was adjusted to get approximately 75 chart units (or 7.5 mV) with the 5 ml sample volume. Thus one recorder division represented 5 ppm CO_2. Further increase in sensitivity was obtained by adjusting sensitivity full scale on the recorder so that it gave 100 units, in which case 1 chart division represented 3.8 ppm. Another method for increasing sensitivity was to change the recorder range from 0 to 10 mV to 0 to 5 mV in which case one recorder unit represented one-half the concentration of the higher voltage selection range. As an example the 5 ppm per division at the 0 to 10 mV would become 2.5 ppm per division at the 0 to 5 mV setting.

The 7.5 mV output for the 5 ml samples volume is not a fixed setting. Thus, 7.5 mV output could be obtained with a 1-, 2- or 3-ml sample volume by proper adjustment of the "sensitivity" selector.

Instrument response was rapid following sample injection. This was in the order of 10 to 15 seconds so that individual samples could be run easily at one-minute intervals.

SUMMARY:

An infrared gas analyzer system suitable for measuring CO_2 in small sample volumes taken from soil flux and photosynthesis studies was set up. Rapid, successive sample analyses could be achieved because of the fast response and recovery of the analyzer system.

REFERENCES:

Clegg, M. D., Sullivan, C. Y., and Eastin, J. D. 1978. A sensitive technique for the rapid measurement of carbon dioxide concentration. Plant Physiol. 62:924-926.

PERSONNEL: F. S. Nakayama, B. A. Rasnick

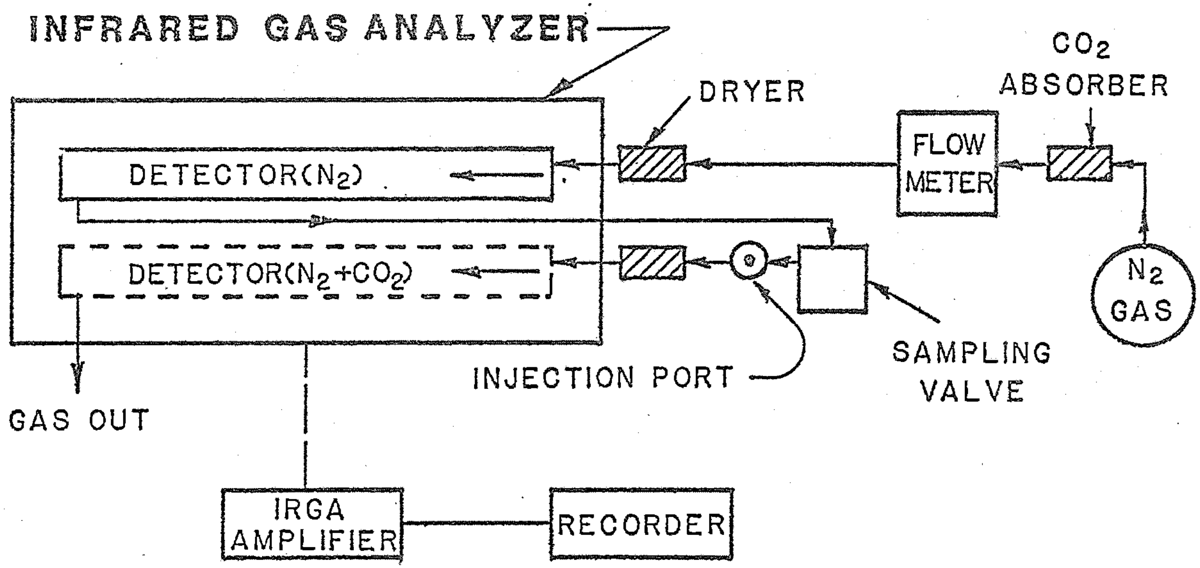


Figure 1. Schematic diagram of infrared gas analyzer system for measuring small volumes of CO_2-containing gases.

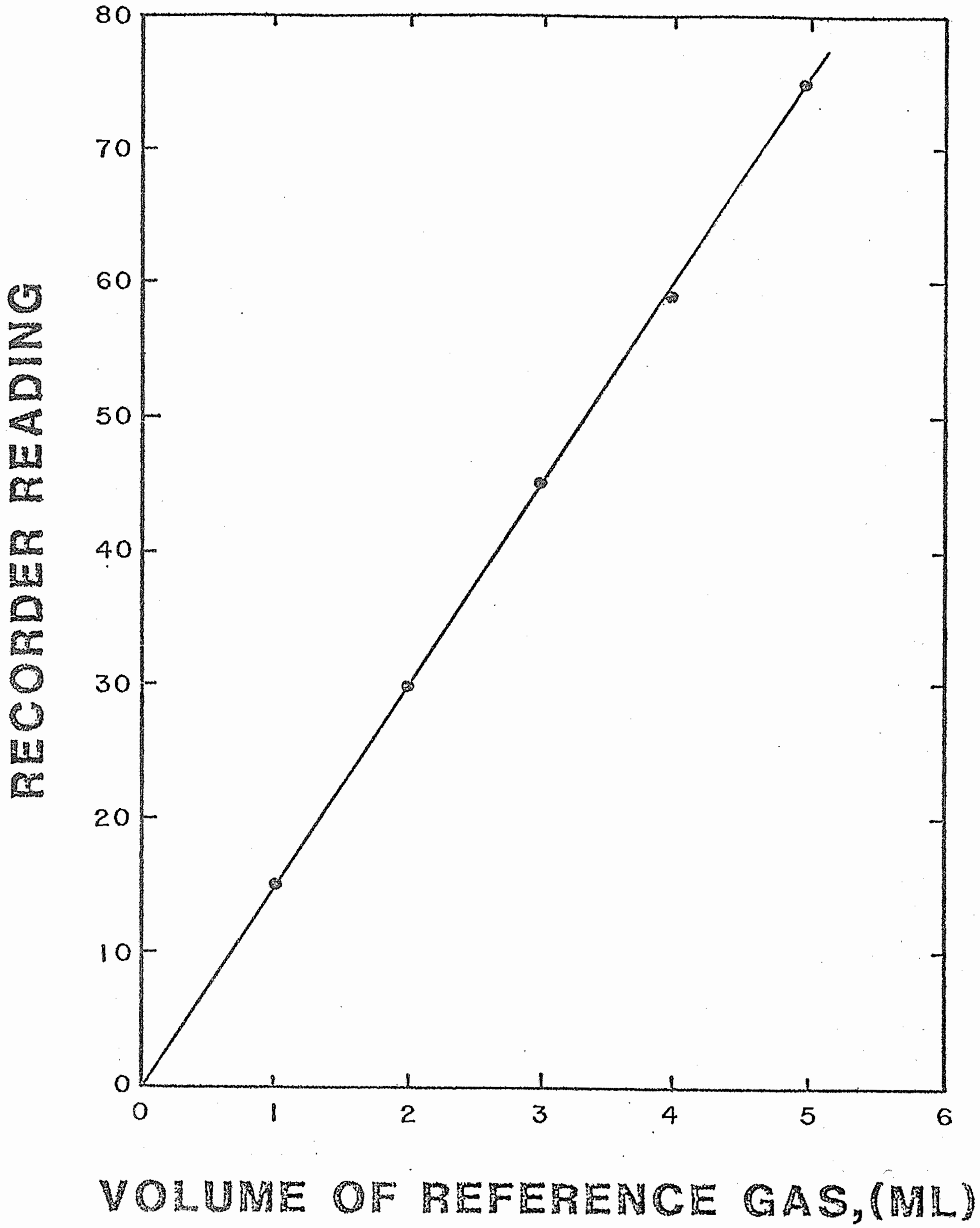


Figure 2. Calibration curve relating recorder output to amount of reference CO_2 gas introduced into the analyzer.

TITLE: DETERMINATION OF CARBON DIOXIDE FLUX FROM SOIL

NRP: 20760 CRIS WORK UNIT: 5510-20760-004

INTRODUCTION:

A knowledge of the carbon dioxide flux from the soil is an important part in understanding the carbon balance of natural and crop production systems. For the establishment of a complete carbon dioxide budget, the soil CO_2 flux must be obtained separately (Monteith et al., 1964). Several methods have been devised for measuring CO_2 and similarly N_2O fluxes using either the open-chamber or close-chamber technique (Kanemasu et al., 1974; Matthias et al., 1980; Ryden et al., 1980; Hutchinson and Mosier, 1979). In the flow-through, open-chamber system, different fluxes have been observed depending on whether the sampling gas stream was blown into or sucked out of the enclosure. The major shortcoming of the closed chamber system is the buildup with time of the diffusing gases within the sampling chamber that affects the flux measurement unless appropriate procedures are taken to correct for this behavior. When the sampling time is held short enough, however, reasonable estimates of the gas flux can be made.

Equipment was built and techniques developed for analyzing small volumes of CO_2 as a means of determining CO_2 fluxes in semi and arid zone soils under irrigation.

MATERIAL AND PROCEDURE:

A 10-cm high, cylindrical chamber was built from polyvinyl chloride pipe with 0.9 cm wall thickness and 20.1 cm inside diameter. The bottom of the cylinder was tapered so that it could be driven into the soil. "Snap-on" type hinged locks were placed on the upper outside edge of the cylinder so that a 10.2 thick, 21.5 cm diameter circular lid made from Plexiglass could be quickly secured over the chamber. Rubber gasket was glued to the lid to provide an air-tight seal between the lid and cylinder. Serum caps were fitted on the lid through pre-drilled holes so that the air in the enclosed chamber could be sampled with gas-tight hypodermic syringes.

The carbon dioxide gas was analyzed with a differential type infrared analyzer (Beckman Model 315A). The analytical procedure used was similar to that described by Clegg et al. (1978). The technique was modified to include a gas sampling valve designed for gas chromatographic equipment so that reproducible gas sample volumes could be injected into the flow stream. Volumes of 1 to 10 ml could be used by selecting the appropriate sampling loop. Predried nitrogen gas at 900 ml/hr was used as the carrier gas. The equipment was calibrated with standard reference CO_2 gas mixtures. Analysis could be made to ± 5 ppm.

For field use, the sampling chamber was installed onto the soil so that a 5 cm distance (h = 5 cm) between the soil surface and the top of the chamber was obtained. An initial 5 ml gas sample was taken just as the cylinder was being fitted into the cylinder top and additional samples taken from the inner chamber through the lid at 0.5 min intervals. The sampled gas mixtures were taken to the laboratory for CO_2 analyses.

A thermocouple sensor was fitted on the soil surface and within the sampling chamber to monitor soil temperature. Where applicable, gravimetric water contents were determined in 1 cm increments to 20 cm. The site selected for the equipment testing was located within a 4-month-old guayule field where the soil was essentially bare.

RESULTS AND DISCUSSION:

Typical CO_2 concentration changes with time for the various sites with different water contents are shown in Figure 1. Samples at sites coded A1, B1 and C1 were taken in the early morning (Table 1) at 0630 and 0700, and C3 was taken at the same site as C1, but at 1230 in the afternoon. The plot of the data shows a linear relation between time and CO_2 concentration in the chamber within the three to five minute elapsed time after the cylinder was enclosed. Statistical analyses of these curves using a final time of three minutes show a good linear fit. The slope, the change in the CO_2 concentrate with time, was used to calculate the flux using the simple relation presented by Kimball (1978)

$$\text{Flux} = h\ (\Delta c/\Delta t)$$

where h is the average height of the sampling chamber above the soil. This derivation also assumed that the increase in CO_2 within the sampling chamber has a negligible effect in the CO_2 concentration gradient within the soil. An elapsed time of one minute gave similar results, but because of only three data points to analyze the data the analyses was not heavily relied upon.

The lower CO_2 fluxes were associated with the lower soil water contents; and where microbial activity is the predominant source of soil-derived CO_2, microbial activity would be low at such water contents. The CO_2 flux increased dramatically as the site was irrigated (sample D-3), and indicating rapid increase in microbial CO_2 production.

SUMMARY AND CONCLUSIONS:

A simple and rapid method for determining carbon dioxide fluxes from soil was developed. Flux measurements could be made one to three minutes after the sampling chamber was installed. The equipment could be used under various soil moisture conditions, even while irrigation was in progress. These flux measurements should provide information on the evolution of CO_2 under natural and irrigated conditions.

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Clegg, M. D., Sullivan, C. Y., and Eastin, J. D. A sensitive technique for the rapid measurement of carbon dioxide concentration. Plant Physiol. 62:924-926. 1978.

Hutchinson, G. L. and Mosier, A. R. Nitrous oxide emissions from an irrigated cornfield. Science 205:1125-1127. 1979.

Kanemasu, E. T., Powers, W. L., and Siji, J. W. Field chamber measurements of CO_2 flux from soil surface. Soil Sci. 118:233-237. 1974.

Kimball, B. A. Critique on application of gaseous diffusion theory to measurement of denitrification. In: Nielsen, D. R. and MacDonald, J. G. (Eds). Nitrogen in the Environment. Academic Press, N.Y., pp. 351-361. 1978.

Matthias, A. D., Blackmer, A. M., and Bremner, J. M. A simple chamber technique for field measurement of emissions of nitrous oxide from soils. J. Environ. Qual. 9:251-256. 1980.

Monteith, J. L., Szeicz, G., and Yabuki, K. Crop photosynthesis and the flux of carbon dioxide below the canopy. J. Appl. Ecol. 1:32127. 1964.

Ryden, J. C., Lund, L. J., and Focht, D. D. Direct in-field measurement of nitrous oxide flux from soils. Soil Sci. Soc. Amer. J. 42:73137. 1980.

PERSONNEL: F. S. Nakayama, B. A. Rasnick

Table 1. CO_2 fluxes at different sites with varying water content and sampling time.

Site		Sampling time	linear correlation coefficient	Flux ($mg/m^2/h$)	Temp. air	Temp. soil	Avg. Water content
A	1	0636	0.99	90.4	26.0	25.0	0-10 cm = 3.2%
	2	0906	0.86	75.6	35.5	32.0	10-20 cm = 6.8%
	3	1200	0.77	69.0	40.4	52.0	20-40 cm = 8.0%
B	1	0651	0.94	83.3	26.5	25.0	0-10 cm = 6.0%
	2	0919	0.88	70.8	35.0	29.0	10-20 cm = 9.0%
	3	1213	0.97	115.4	42.5	47.5	20-40 cm = 8.5%
C	1	0705	0.99	152.2	27.5	22.0	0-10 cm = 21.6%
	2	0932	0.92	172.6	36.0	31.5	10-20 cm = 22.4%
	3	1226	0.96	213.1	42.5	51.5	20-40 cm = 25.0%
D	1	0718	0.97	102.5	27.5	22.0	0-10 cm = 2.1%
	2	0945	0.92	130.8	36.0	29.5	10-20 cm = 3.8%
	*3	1239	0.97	286.4	44.0	37.5	20-40 cm = 10.8%

* Site just being irrigated.

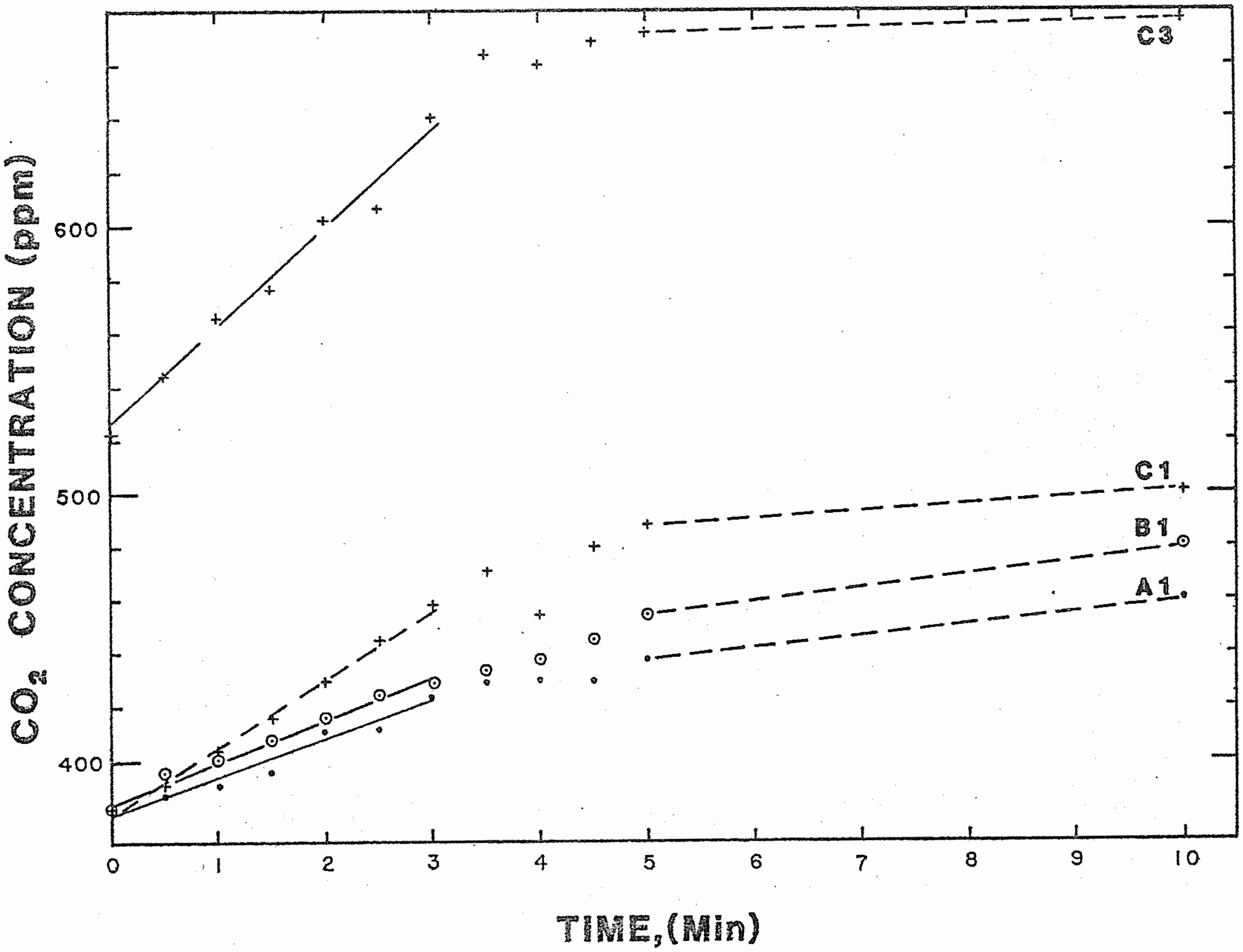

Figure 1. Carbon dioxide changes with time in sampling chamber.

TITLE: EVALUATION OF CO_2-ENRICHED, UNVENTILATED, SOLAR-HEATED GREENHOUSES

NRP: 20760 CRIS WORK UNIT: 5510-20760-004

INTRODUCTION:

The benefits from growing plants in unventilated greenhouses are potentially very large. The greenhouse cover slows the loss of water, so plants can be grown in arid regions. High light intensity and long duration of sunshine in such regions are conducive to high crop yields, particularly when the greenhouses are enriched with CO_2. Therefore, this project was started with the objectives: 1. to design, test, and evaluate coolers for unventilated greenhouses under summertime conditions; 2. to design, test, and evaluate methods of solar energy storage as a means to achieve satisfactory heating in wintertime and cooling in summertime of unventilated greenhouses; 3. to evaluate the yield responses attainable with CO_2 enrichment in unventilated greenhouses; and 4. to evaluate alternative sources of CO_2 for fertilizer.

Over the past 3 years, several experimental crops of tomatoes were grown in conventional ventilated, ambient CO_2 greenhouses and in unventilated, CO_2-enriched greenhouses. The yields from these experiments were generaly higher than reported by previous workers. The yields of spring crops from its unventilated houses enriched to 1000 µl/l CO_2 were about 14 kg/plant, which apparently is a record. The unventilated, CO_2-enriched houses yielded 20-50% more than the conventional with spring crops but not with fall crops.

The yield experiments fulfill objective 3, at least for tomatoes. Therefore, the emphasis has shifted toward objectives 2 and 1 with the evaluation of the solar energy storage and coolers being done by computer model. Additional experimental data are being obtained for use in model verification. Some of these data for 1. an unheated, uncooled greenhouse, 2. a conventional greenhouse, 3. a solar greenhouse with passive water storage, and 4. a solar greenhouse with active water storage are presented in this report.

PREDICTION OF SKY THERMAL RADIATION

The greenhouse computer model used in this project as well as most computer models of energy-related structures or crops need to know the amount of thermal radiation emitted from the sky, which on a daily basis can exceed the amount of solar radiation. Thermal radiation is not recorded by the National Weather Service, and therefore it must be predicted from the data they do record. Idso (1980) previously developed equations for predicting thermal radiation for clear skies using air temperature and vapor pressure. Building on his clear sky equations, a mathematical model for predicting thermal radiation from cloudy skies was developed.

The model used previous clear-sky equations for predicting full spectrum sky emittance and 8-14 μm atmospheric window transmittance, and then assumes that the cloud contribution to sky thermal radiation must be transmitted to the earth's surface through the atmospheric window. The model uses surface vapor pressure, surface temperature, cloud amount, cloud type, and cloud height data as recorded by National Weather Service observers. Using the model, upper limits of the cloud contribution to sky radiation were derived. For Phoenix, Arizona, the upper limit was about a 40% increase for 100% sky cover. The average predicted increase due to clouds for times in 1978 with 100% sky cover was about 18%.

Actual measurements of sky thermal radiation were made in Phoenix and in Sidney, Montana, for a wide range of weather condtions, and these measurements were compared to model predictions computed from NWS data for corresponding times. Agreement between predicted and measured values was good. On an hourly basis, the overall R^2 was 0.89 and the linear regression slope was 0.99. On a daily total basis, the overall R^2 was 0.94 and the slope was 0.97. Agreement was actually better under partly cloudy skies than under clear skies. Under overcast skies, the agreement was poorer, but the temperature range represented by the data was smaller.

PREDICTION OF SOLAR RADIATION

As with sky thermal radiation, solar radiation is not routinely measured by all National Weather Service stations, and therefore, it must be predicted for use in the greenhouse model, as well as for use in many other models in many other fields. As recommended by the ASHRAE Task Group on Energy Requirements for Heating and Cooling (1975), the solar radiation model of Kimura and Stephenson (1969) was chosen. Using sun angle equations, sky cover as recorded by the NWS, and geographical "clearness" numbers, their model can be used to predict total and diffuse solar radiation on surfaces with any tilt angle.

To test the accuracy of the Kimura and Stephenson solar radiation model, comparisons were made between predicted and measured values for a horizontal surface for selected times during 1978 in Phoenix. The hourly values are presented in Figures 1, 2 and 3 for clear, partly cloudy, and overcast skies. For clear skies the agreement is excellent (R^2 = 0.99) with the values clustered along the 1:1 line. For partly cloudy skies its agreement is much worse (R^2 of 0.81). Obviously the model can over- or under-predict by a factor of 2 depending on whether or not the sun happened to be behind the clouds. For overcast skies, the relative error is similar to the partly cloudy skies, but the absolute error is quite small at these low radiation levels.

The comparisons between predicted and measured daily total solar radiation are presented in Figures 4, 5, and 6. The agreement for the clear sky in Figure 4 is excellent (R^2 = 0.99). The agreement for partly cloudy sky (Figure 5) is good (R^2 = 0.93), and there is considerably less scatter than for the hourly values (Figure 2). There were only 5 days that were completely overcast in 1978 in Phoenix (Figure 6). These data do not follow the 1:1 line, but nevertheless, the absolute error is small at these low radiation levels.

OVERALL HEAT TRANSFER COEFFICIENT

During 1978, soil heat flux G (W/m^2), and the fraction of each hour, f, that the electrical heaters were on was recorded for Greenhouses 2 and 3. These data were used to calculate the overall heat transfer coefficient, U ($W/m^2 \cdot C$) for these fiberglass greenhouses. The equation used to calculate U was:

$$U = \frac{GA_g + fH}{A_c(T_{ai} - T_{ao})}$$

where A_g is the soil area (27 m^2), A_c is the exposed cover area (42 m^2 for GH 3 and 57 m^2 for GH 2), H is heater capacity (W), and ($T_{ai} - T_{ao}$) is the difference in temperature between the inside and outside air.

The U values for nighttime hours where $T_{ai} - T_{ao}$ was greater than 1°C are plotted in Figure 7 against wind speed. The data exhibit a slight dependence on wind speed, but the correlation is low ($R^2 = 0.39$ for GH 2 and 0.41 for GH 3) due to the large scatter. Most of the data points are above the dashed line at 7.5, which was estimated using guidelines proposed recently by the American Society of Agricultural Engineers Structures and Environment Committee 303. The ASAE line includes infiltration but probably is based on data that included only heater output and no soil heat flux. Ignoring soil heat flux would bring the data points closer to the ASAE line.

GREENHOUSE HEATING AND COOLING SYSTEMS

The first and second objectives of this project are concerned with evaluation of methods for cooling and solar heating greenhouses. The primary tool for these tasks is the MEB computer model. However, as with any such model, actual performance data are needed to validate the model and to provide values for some of the parameters. Therefore, the four test greenhouses that were used for the previous CO_2 enrichment studies were modified to represent four different heating-cooling systems.

The 27 m^2 fiberglass greenhouses have been described in previous reports. Greenhouse 2 is the conventional fan-pod cooled greenhouse with an electrical heater. The cooling and heating thermostats were set at 26.5°C (80 F) and 15.5°C (60 F), respectively. Greenhouse 4 was connected to the solar energy storage water tank described in last year's report. In wintertime solar energy was collected from the greenhouse whenever the greenhouse air temperature is higher than 24°C (75 F), and then when the greenhouse temperature dropped below 15.5°C (60 F) solar energy was brought back from storage. An auxilliary electric heater was in the greenhouse with its thermostat set at 13°C (55 F). In summertime solar energy was collected when the greenhouse temperature exceeded 26.5°C (80 F) and then it was dumped to a cooling tower whenever the tank temperature exceeded the outdoor wet bulb temperature by more than 2°C as determined by a differential thermostat. The air-water heat exchanger in the greenhouse and the media in the cooling tower were both wetted aspen excelsior pods, as described in the 1977 Annual Report. The installation of the tank and associated plumbing and wiring and instrumentation were completed in September, and data were collected from Greenhouses 2 and 4 from about the first of October.

After the "active" solar heating system was installed on Greenhouse 4, 576 1-gallon plastic bottles were filled with water and stacked in Greenhouse 1 to make a "passive" solar heating system. The total volume of water was 2.2 m^3 or 0.081 m^3 of water per m^2 of greenhouse. The overall dimensions of the stack were 1.3 m wide by 1.9 m long by 2.0 m high = 4.9 m^3, so 45% of the stack was water. About 8% of the stack volume was wood supporting structure leaving 47% air. Neglecting the bottoms and the caps, the heat exchange area per bottle was 1270 cm^2. Some of the bottles touched one another decreasing the heat exchange area by an estimated 20%, so the total heat exchange area was about 59 m^2.

Greenhouse 3 was an unheated and uncooled control greenhouse. Data collection from Greenhouses 1 and 3 started on about 1 December.

GREENHOUSE THERMAL PERFORMANCE ON A DAILY BASIS

The energy use results for conventional Greenhouse 2 are presented in Figure 8. There was a rather abrupt change from summer to winter in 1980 on 15 October. Abnormally warm fall weather suddenly yielded to a cold front. This can be seen in Figure 8 when the energy consumed by the fan and pump for the evaporative dropped from 1.5 MJ m^{-2} day^{-1} to about 0.2, while heater energy use went from 0.0 to 1.0 overnight. Even more dramatic in Figure 2 is the change in solar energy while closed. During the first half of October, about 1.0 MJ m^{-2} day^{-1} was received outside while the greenhouse was unventilated, and then it changed to about 14 as the cooler weather made it unnecessary to ventilate the greenhouse more than a few hours each day. December was unusually mild and only about 7 MJ m^{-2} day^{-1} of heater energy was required per day compared to 10 in the past years.

The energy use results for active solar Greenhouse 4 are presented in Figure 9. No ventilation or auxilliary heat were required in Greenhouse 4. The solar collected data were computed from positive temperature changes of the solar tank water, while the solar used data were computed from negative changes. During the first half of October while the cooling tower was in operation, these data were very erratic. Some of the milder recorded temperature changes occurred at the time of starting and stopping of the cooling tower, so evidently the tank layers were not well mixed and certain thermocouples were affected more than others. An elbow will be placed in the discharge pipes to be sure that the water returning to the tank from the cooling tower or greenhouse is directed away from the tank temperature sensors.

The solar system provided 100% of the heating requirement for this mild winter. The electric power required for the fan and pump amounted to about 1/3 to 1/2 that required by the heater in Greenhouse 2. This is a significant energy savings, but one must remember that the pumps and fan in the solar system require electricity, whereas the heater in Greenhouse 2 could have used a cheaper form of energy than electricity. However, the sizing of the components in the active solar system probably is not optimal, and these data are for validation of the computer model.

The air temperatures for Greenhouses 2 and 4 are presented in Figures 10 and 11. These data are as expected for greenhouses with active thermostatic temperature control. The air temperatures for Greenhouses 3 and 1 are presented in Figures 12 and 13, and here the air temperature ranges are much greater. The maximums of 30 to 39 C are too high and the minimums of 4 to 8 C are too low for optimal growth of most crops. The recorded minimum air temperatures for the two greenhouses were very close to the outside minimum, which is puzzling because one would expect them to be a little warmer.

The daily water use by Greenhouses 2 and 4 is shown in Figure 14, as calculated from make-up water meter readings for the evaporative cooler on Greenhouse 2 and the solar energy storage tank on Greenhouse 4. The readings were taken at the start of most working days, so some of the points are 3-day averages. The water use of Greenhouse 2 was about 22 mm per day for the first half of October and then it dropped to about 5. This water was for cooling, as there were no crops in the greenhouses. The water use for Greenhouse 4 was about 35 mm/day for the first part of October and then it dropped to almost 0 when the cooling tower was turned off.

GREENHOUSE THERMAL PERFORMANCE ON AN HOURLY BASIS

The MEB computer model performs simulations on an instantaneous basis, and to get daily values, these instantaneous results must be integrated. For practical purposes the time step is expected to be about an hour in order to provide adequate representation of the changing meteorological conditions.

To provide data for model validation on this hourly time scale, more intensive measurements were taken on 11 December 1981. These measurements mainly consisted of using an infrared thermometer to obtain the outer cover, inner cover, wall, and soil surface temperature in each of the four greenhouses. The measurements were taken manually starting at about 25 minutes after the start of each hour, and about 10 minutes were required to obtain all of them. Taking the measurements on the half hour as we did, placed the observation time in the middle of the averaging period used by the Autodata-9 for the automatically acquired data. The manual measurements were started at 0630 on 11 December 1980 and stopped at 0730 on 12 December. At about 1030 and 1400 the sand soil surfaces were wetted with water from the hose to represent the wet surfaces usually encountered in production greenhouses. This may have been an unwise choice, however, because conditions were changing more rapidly than desired for data intended to provide a reliable standard to compare model results against.

The energy use results are presented in Figure 15 for conventional Greenhouse 2 and in Figure 16 for active solar Greenhouse 4. The hourly rates follow the same relative pattern as the daily rates in Figures 8 and 9. Therefore, models that successfully predict these hourly patterns can reasonably be exptected to successfully predict daily and annual energy use with integration of their hourly results.

The soil, side wall, inside cover (ceiling), and outside cover (roof) temperatures that were measured with the infrared thermometer are presented in Figures 17, 18, 19, and 20 for conventional Greenhouse 2, active solar Greenhouse 4, unheated and uncooled Greenhouse 3, and passive solar Greenhouse 1. The temperatures generally seem reasonable, except that the difference between inside and outside cover temperature seems high, considerly only a thin piece of fiberglass lies between them. This could be partially due to the fact that there is some reflected sky radiation in the outer cover measurement, but there is an even larger amount of reflected soil radiation in the inside cover measurement.

The air temperature and humidity ratios inside all the greenhouses as well as outside are presented in Figures 21 and 22. These data were obtained from psychrometers connected to the Autodata-9. The temperatures all appear reasonable, but the humidity ratios for Greenhouse 3 appear suspiciously high, particularly in comparison with Greenhouse 1 which had comparably high temperatures. It seems likely that the wet bulb was only partially wetted, especially since this definitely happened to the psychrometer in Greenhouse 2. No humidity ratios are plotted in Figure 22 for Greenhouse 2 for these midday times. Overall these data from a variety of greenhouse types should provide a good comparison for the model predictions.

SUMMARY AND CONCLUSIONS:

A mathematical model was developed for predicting thermal radiation from cloudy skies. The model is accurate and has a sound physical base. It uses surface and sky weather data routinely recorded by the National Weather Service. The model is important because the earth's surface receives about as much radiant energy per day from the sky as it does from the sun, and therefore, accurate predictions are needed in studies of earth climate change and crop evapotranspiration and in this project's study of greenhouses heating and cooling.

Solar radiation data that were obtained in 1978 were reduced and compared to predictions made with the model of Kimura and Stephenson (1969). The agreement was excellent on clear days (R^2 = 0.99) and go on partly cloudy days (R^2 = 0.93). Because the National Weather Service has not routinely measured solar radiation, and because solar radiation is a very important weather input for the MEB computer model, an accurate prediction method is necessary. These high correlations show that the Kimura and Stephenson model will generate the accurate solar data required by the MEB model.

Overall heat transfer coefficients (U) were calculated from measurements of temperatures, soil heat flux, and heater operating times for many nights during 1978 in Greenhouses 2 and 3. Both greenhouses were essentially conventional fiberglass greenhouses as far as their heating systems were concerned. The coefficients ranged from about 8 to 12 $W\ m^{-2}\ C^{-1}$. This is higher than the 7.5 value recently proposed as the guide for computing heat loss from fiberglass greenhouses by the ASAE SE-303 Committee, indicating their value may be somewhat low.

During 1980 an insulated water tank was connected to a direct contact, aspen pad heat exchanger in a test greenhouse to create an active solar heating system. Excess solar energy was collected during the daytime and stored in the tank for heating the greenhouse at night, or in hot weather to dump to a cooling tower at night. Near the end of 1980, plastic bottles of water were stacked in another greenhouse to form a passive solar heating and cooling device. Another greenhouse was conventionally heated and cooled, and a fourth greenhouse was not heated or cooled. Energy and water use and temperature data were obtained for all four greenhouses for use in validating the MEB computer model.

The operational results showed that the active solar greenhouse required about 1/3 the energy of the conventional greenhouse. However, this energy was expensive electrical energy used by the fan and pump. The passive solar greenhouse did not consume any energy, but the maximum temperatures were too high, and the minimums too low for optimal growth of most crops. These results for solar greenhouses are discouraging, but the active system was oversized for experimental reasons and therefore the components are not the optimum size. Furthermore, no thermal blankets or other energy conservation techniques were used in either greenhouse. The primary objective to obtain simultaneous data for four very different greenhouse types was achieved, and these data can now be compared with both hourly and daily model predictions. The validated greenhouse model will be used to evaluate the feasibility of using closed greenhouses in arid environments to grow crops with little water. It could also be used to size components for optimal design of solar heating systems.

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PERSONNEL: B. A. Kimball, S. T. Mitchell, and G. Brooks

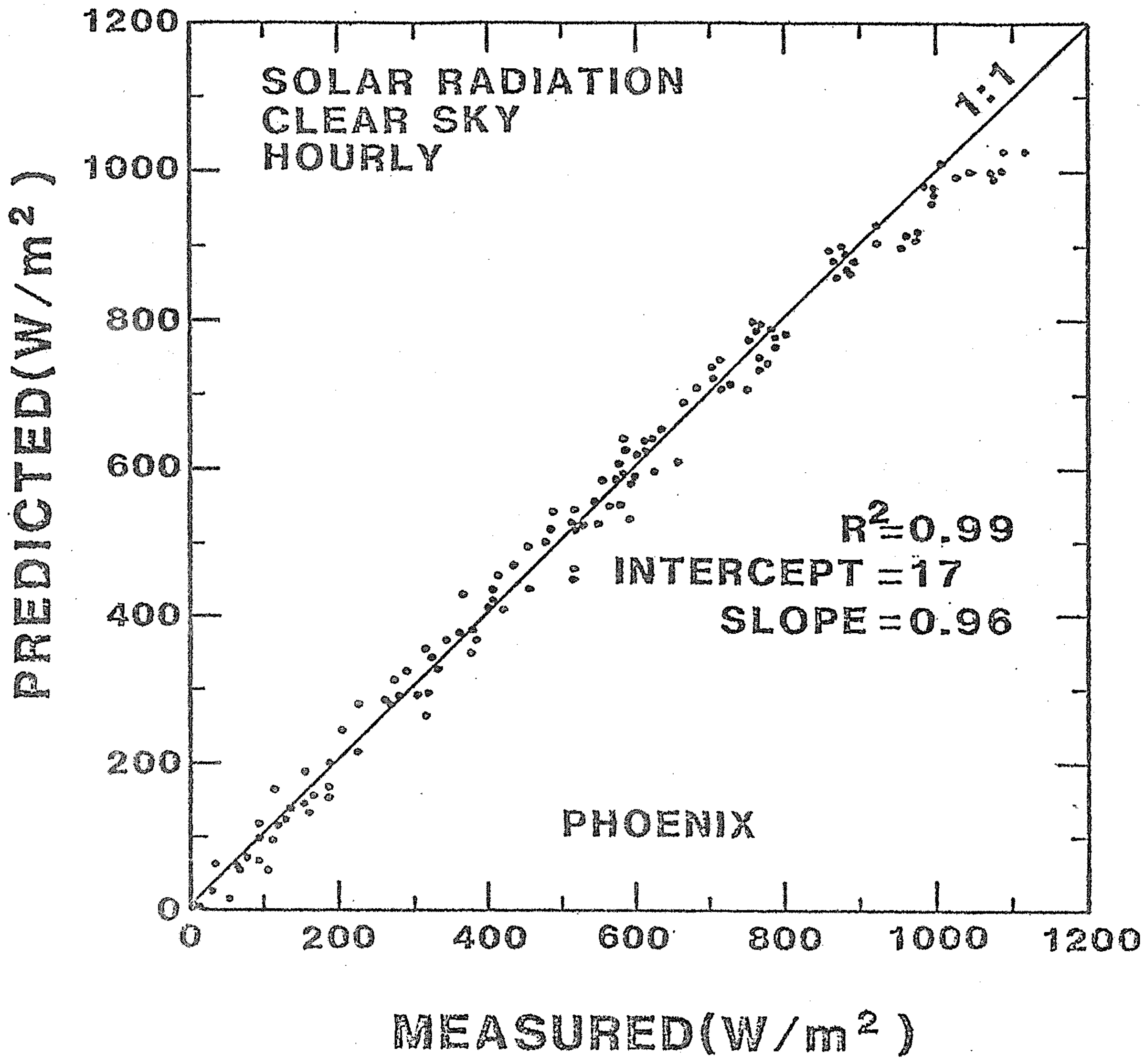

Figure 1. Measured vs. predicted hourly solar radiation for 26 Jan, 23 Feb, 24 Mar, 26 Apr, 16 May, 11 Jun, 16 Aug, 19 Sep, 14 Oct, 16 Nov, and 20 Dec 1978. All days were clear.

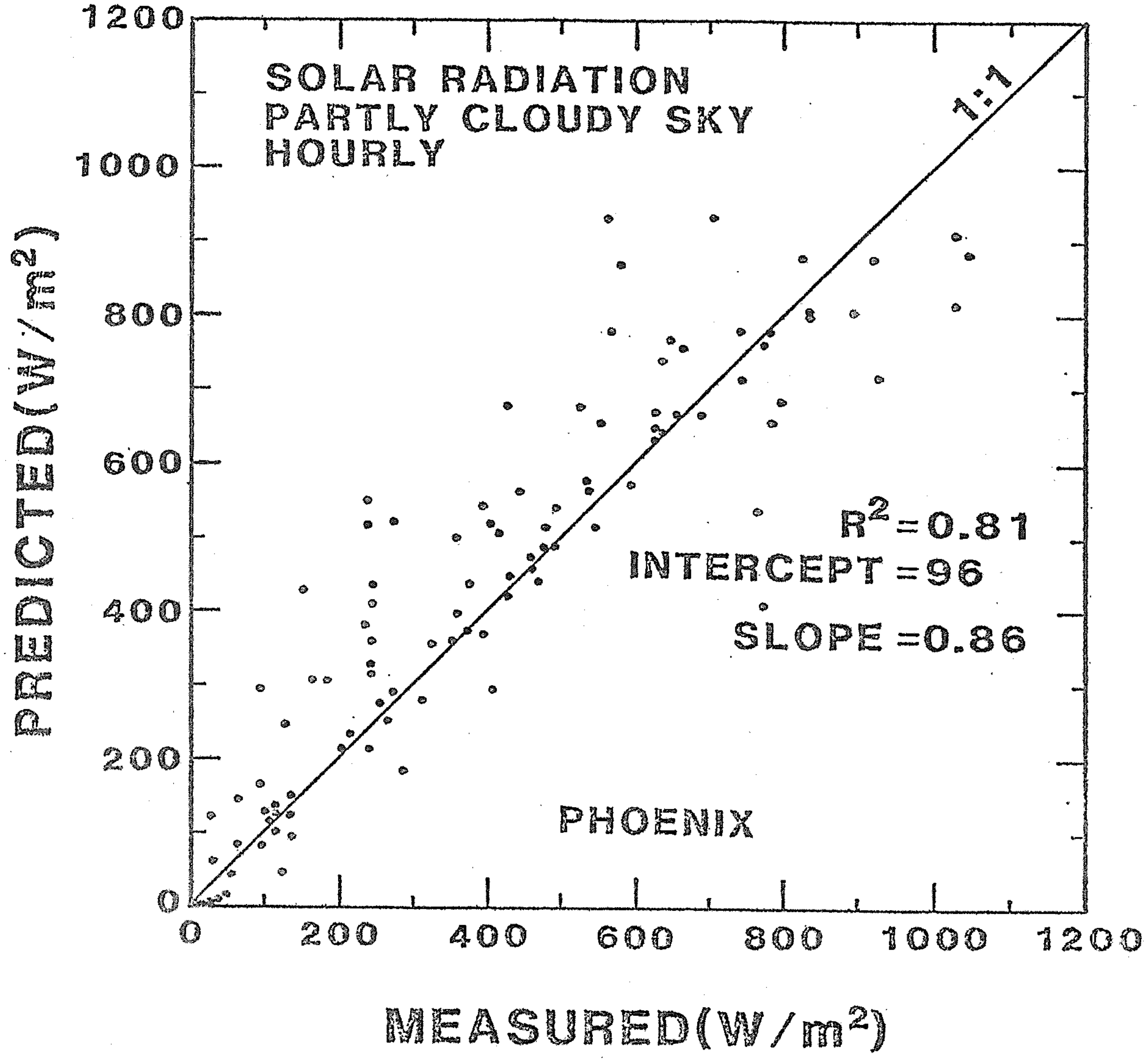

Figure 2. Measured vs. predicted hourly solar radiation for 27 Jan, 26 Feb, 20 Mar, 4 Apr, 25 May, 19 Aug, 16 Sep, 22 Nov, and 16 Dec 1978. All days had about 50% cloud cover.

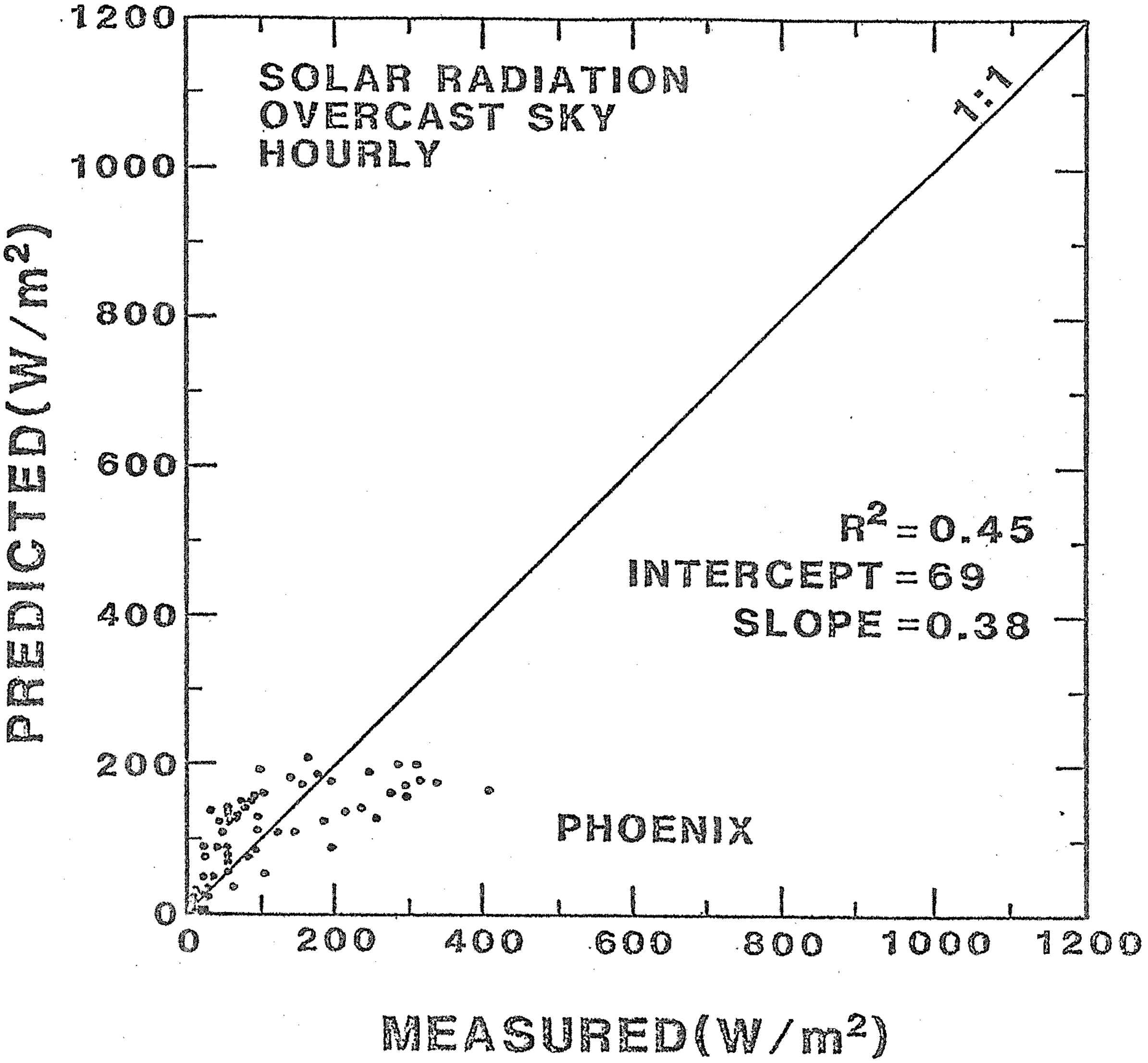

Figure 3. Measured vs. predicted hourly solar radiation for 30 Jan, 28 Feb, 2 Mar, 20 Oct, 12 Nov, and 18 Dec 1978. All days were overcast.

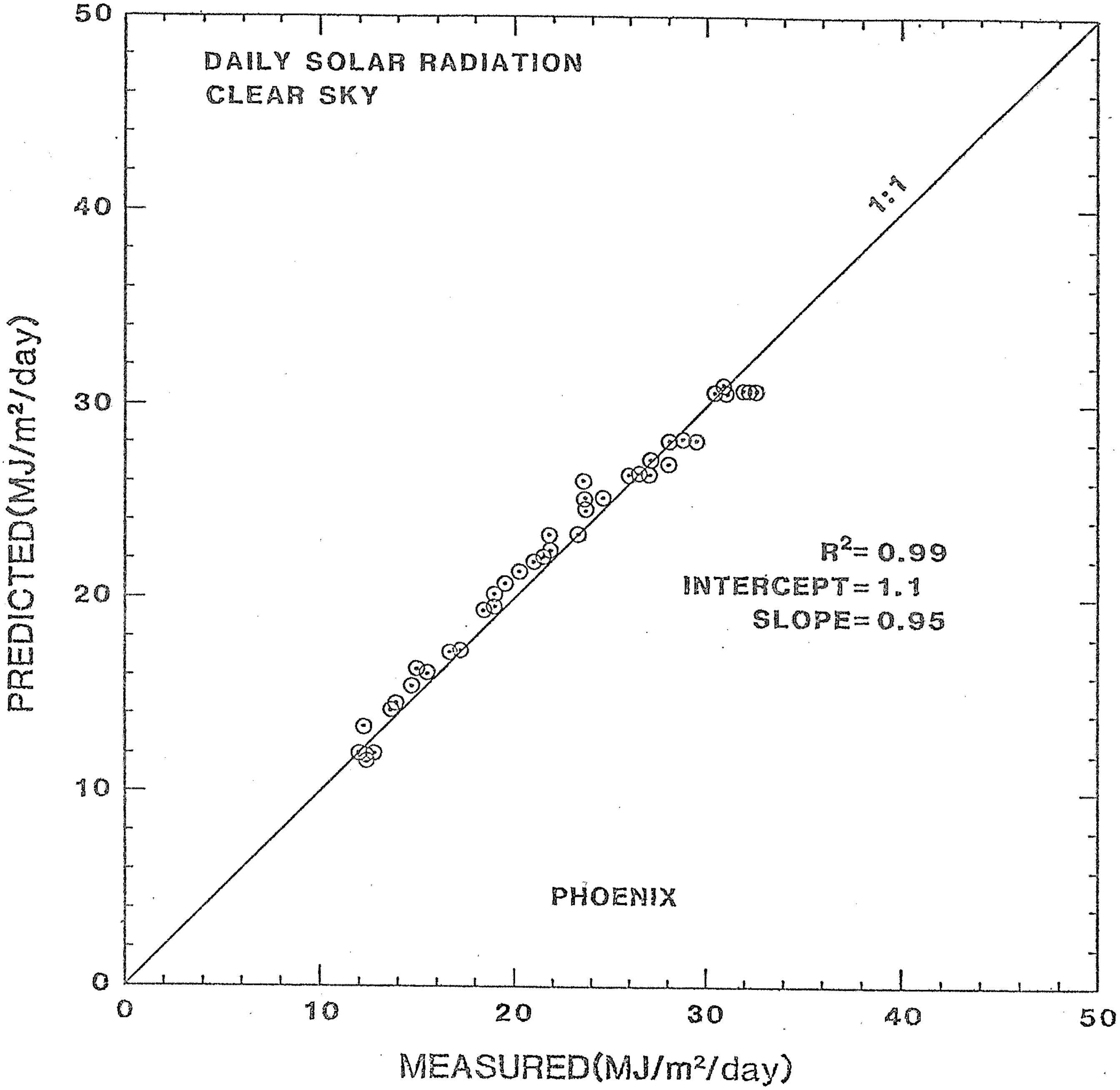

Figure 4. Measured vs. predicted daily solar radiation for clear days in 1978 in Phoenix.

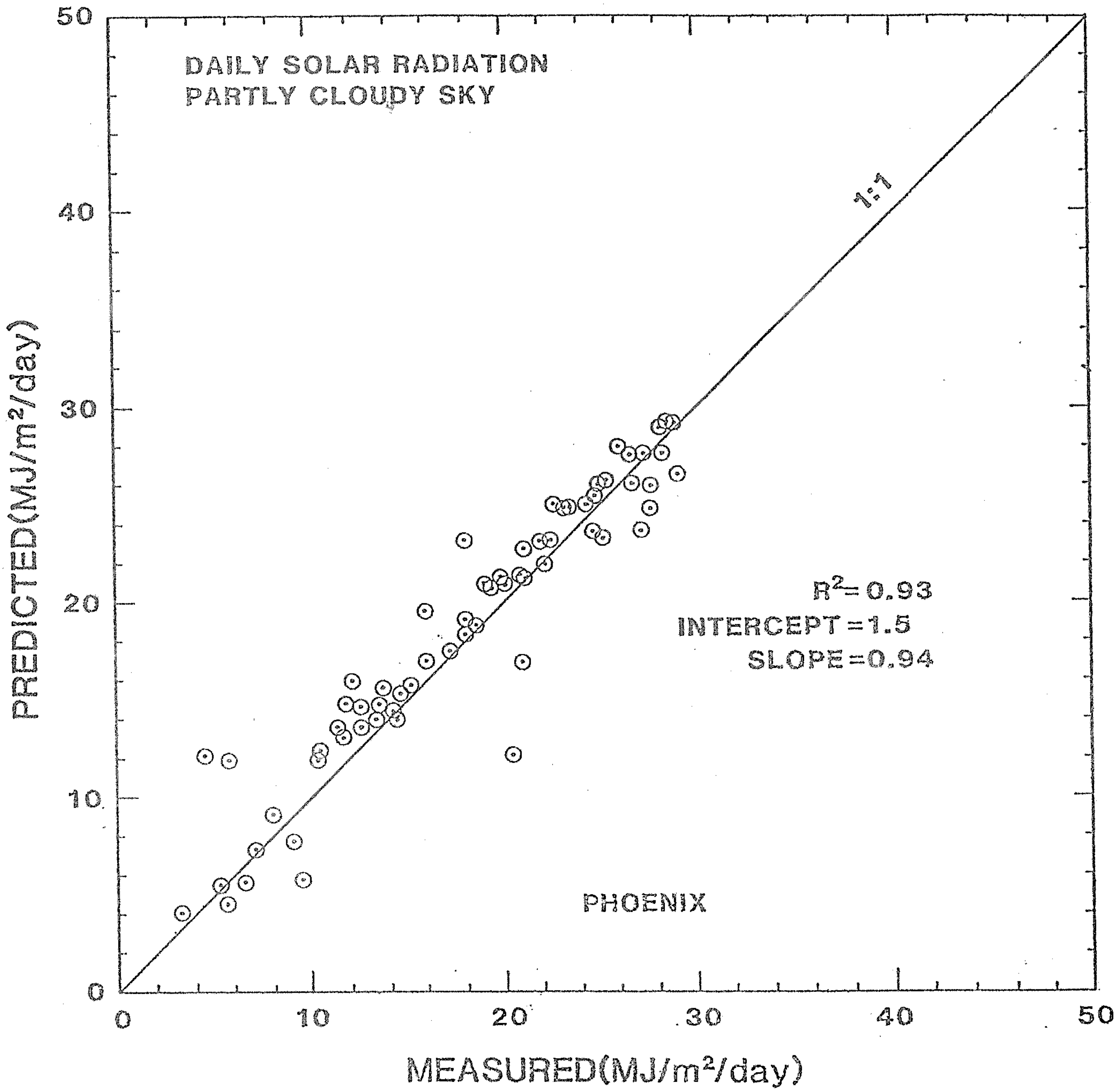

Figure 5. Measured vs. predicted daily solar radiation for partly cloudy days in 1978 in Phoenix.

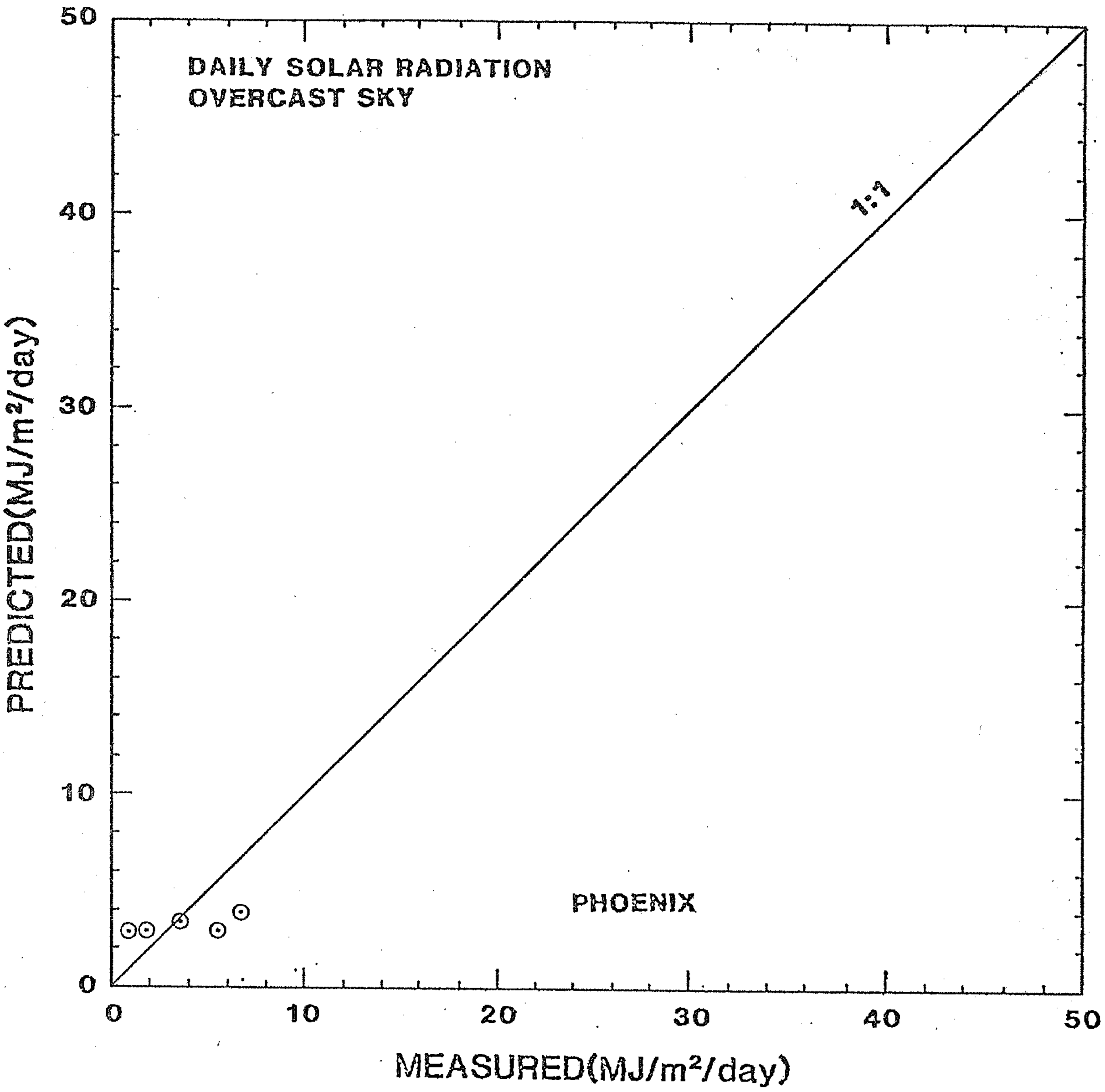

Figure 6. Measured vs. predicted daily solar radiation for overcast days in 1978 in Phoenix.

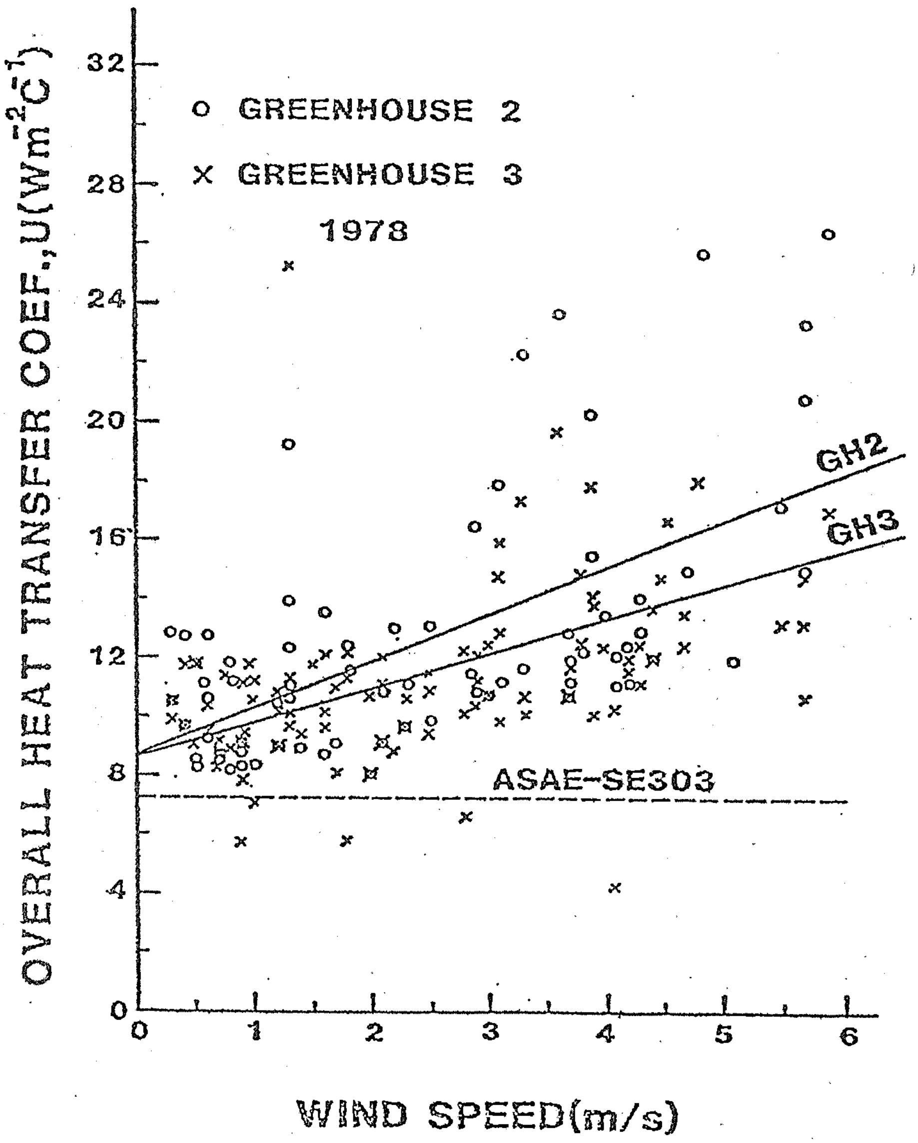

Figure 7. Overall heat transfer coefficients (U) including soil and heater energy vs. wind speed for Greenhouses 2 and 3 and for nights in 1978.

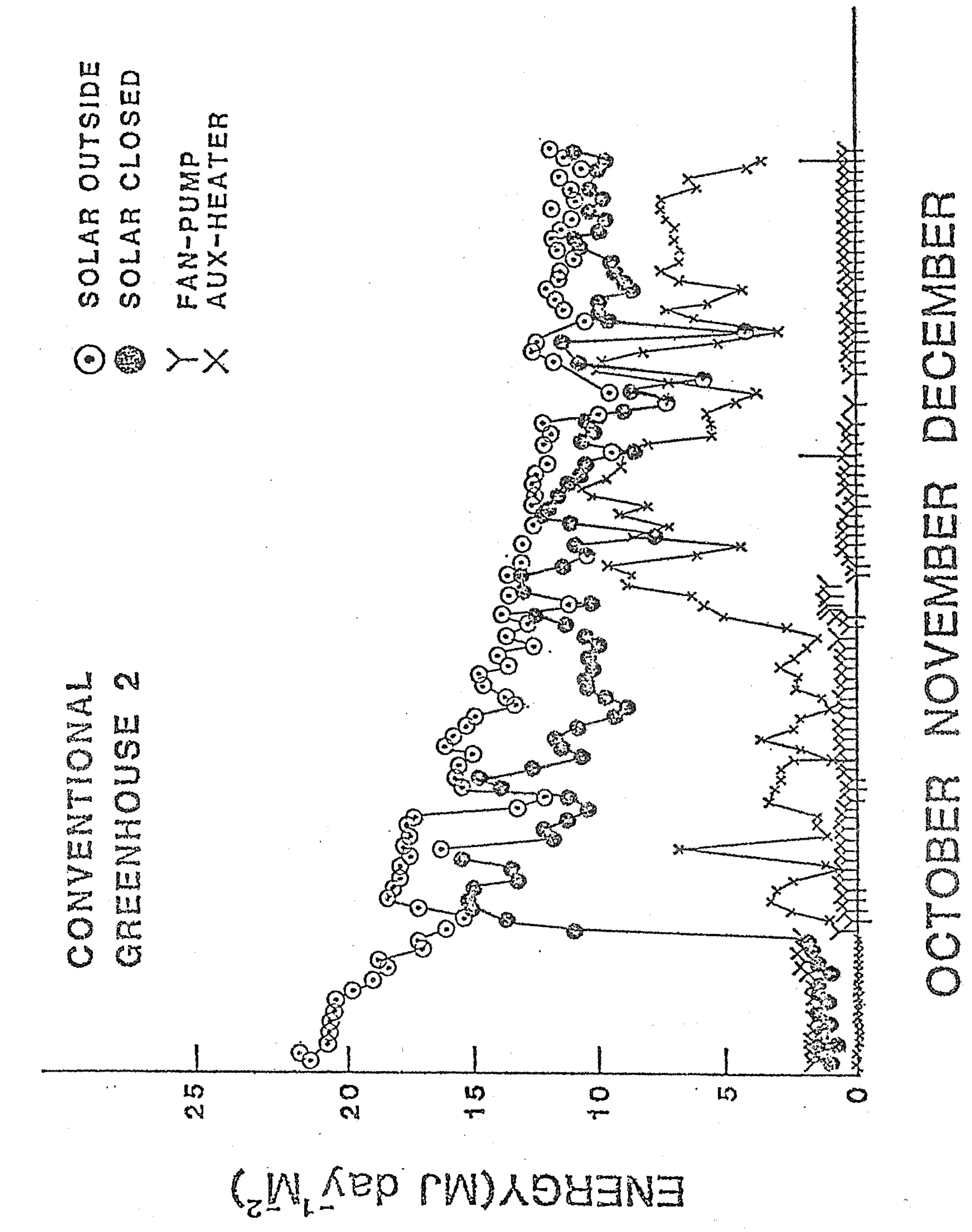

Figure 8. Energy use in conventional Greenhouse 2 in 1980. The solar closed points are the amounts of solar energy received outside while the greenhouse was not ventilated and could have been enriched with CO_2.

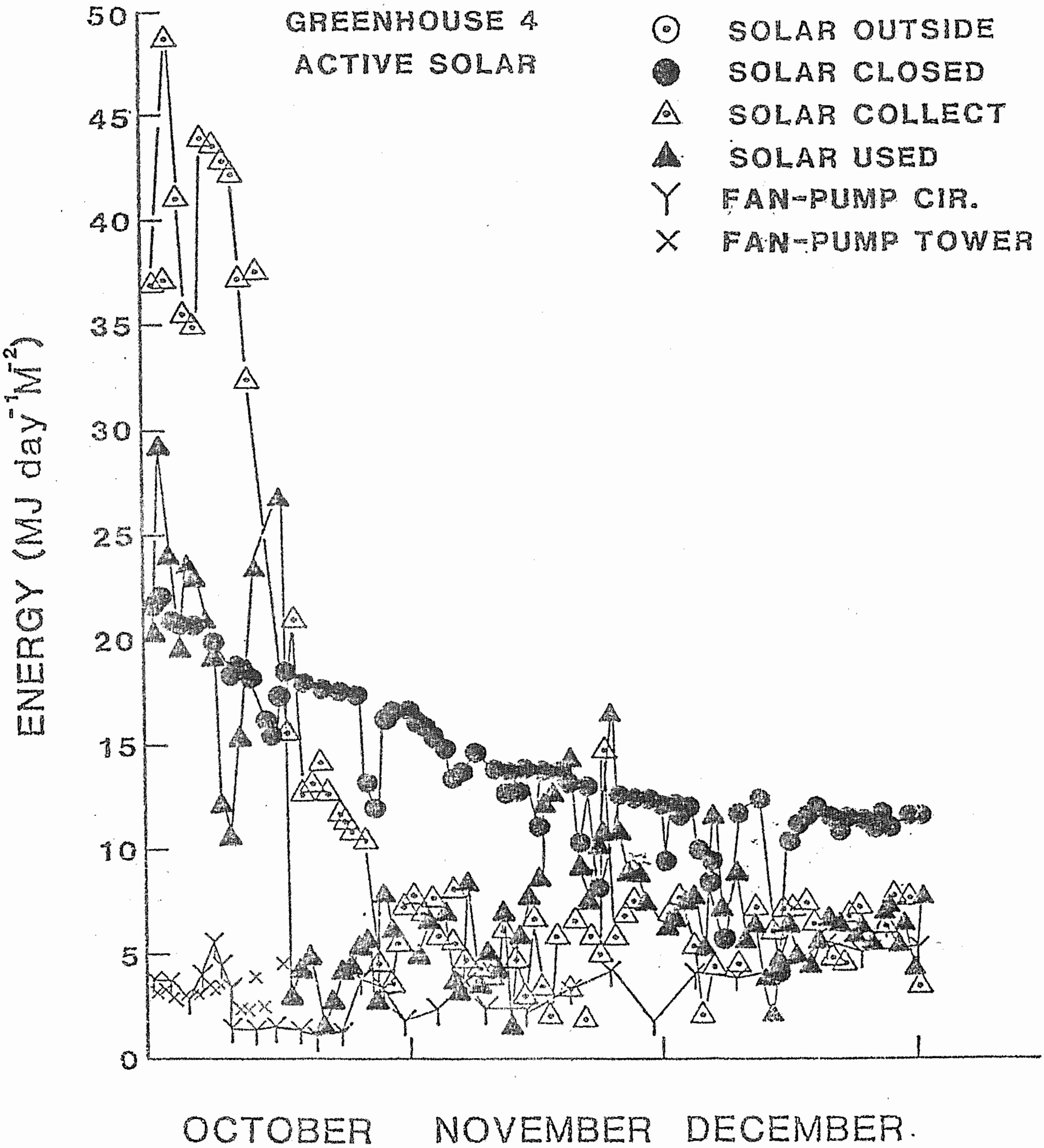

Figure 9. Energy use in active solar Greenhouse 4 in 1980. The greenhouse never required ventilation, so the solar outside point are superimposed on the solar closed points. No auxilliary energy was required.

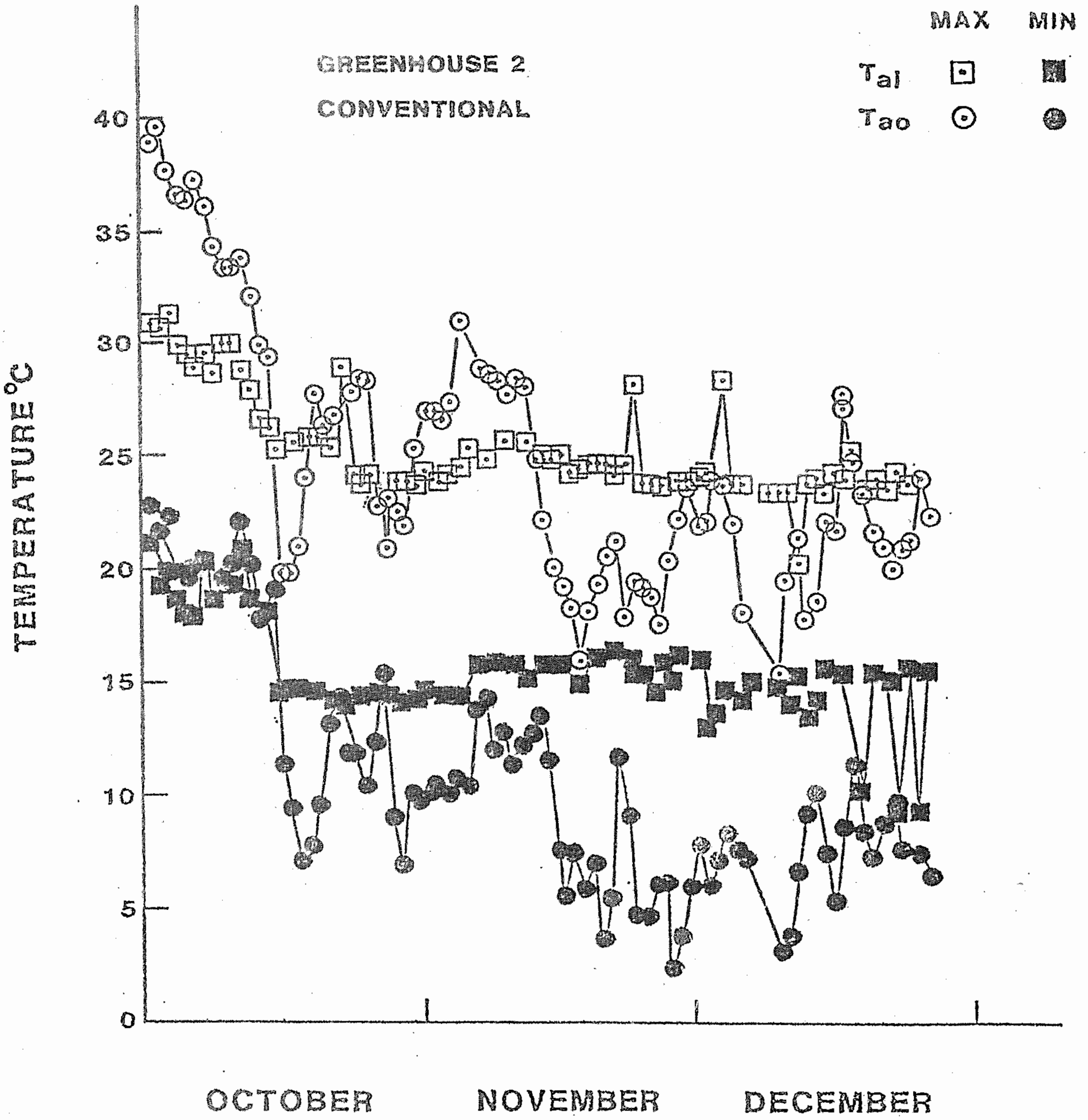

Figure 10. Maximum and minimum temperatures in conventional Greenhouse 2 in 1980.

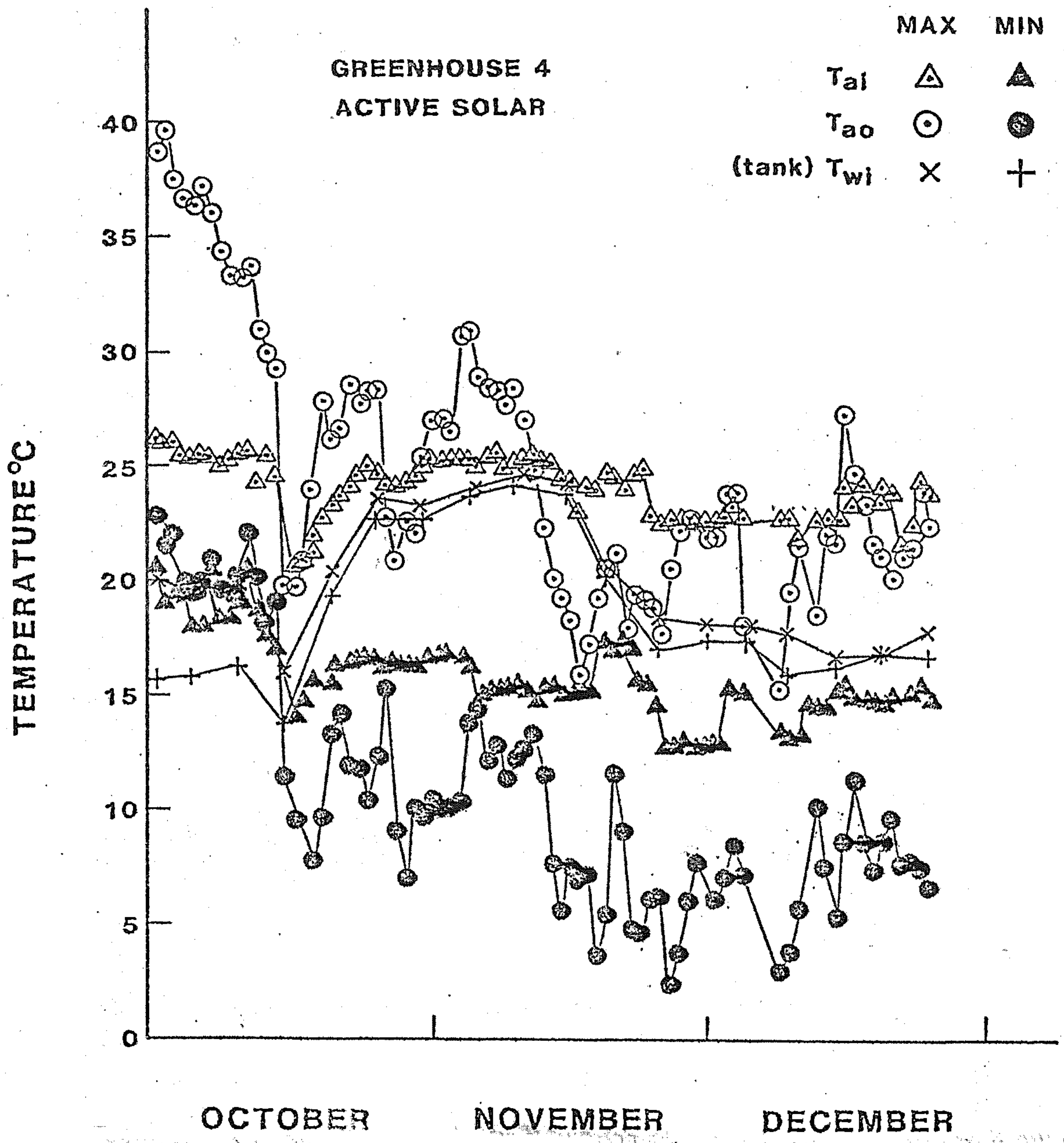

Figure 11. Maximum and minimum temperatures in active solar Greenhouse 4 in 1980.

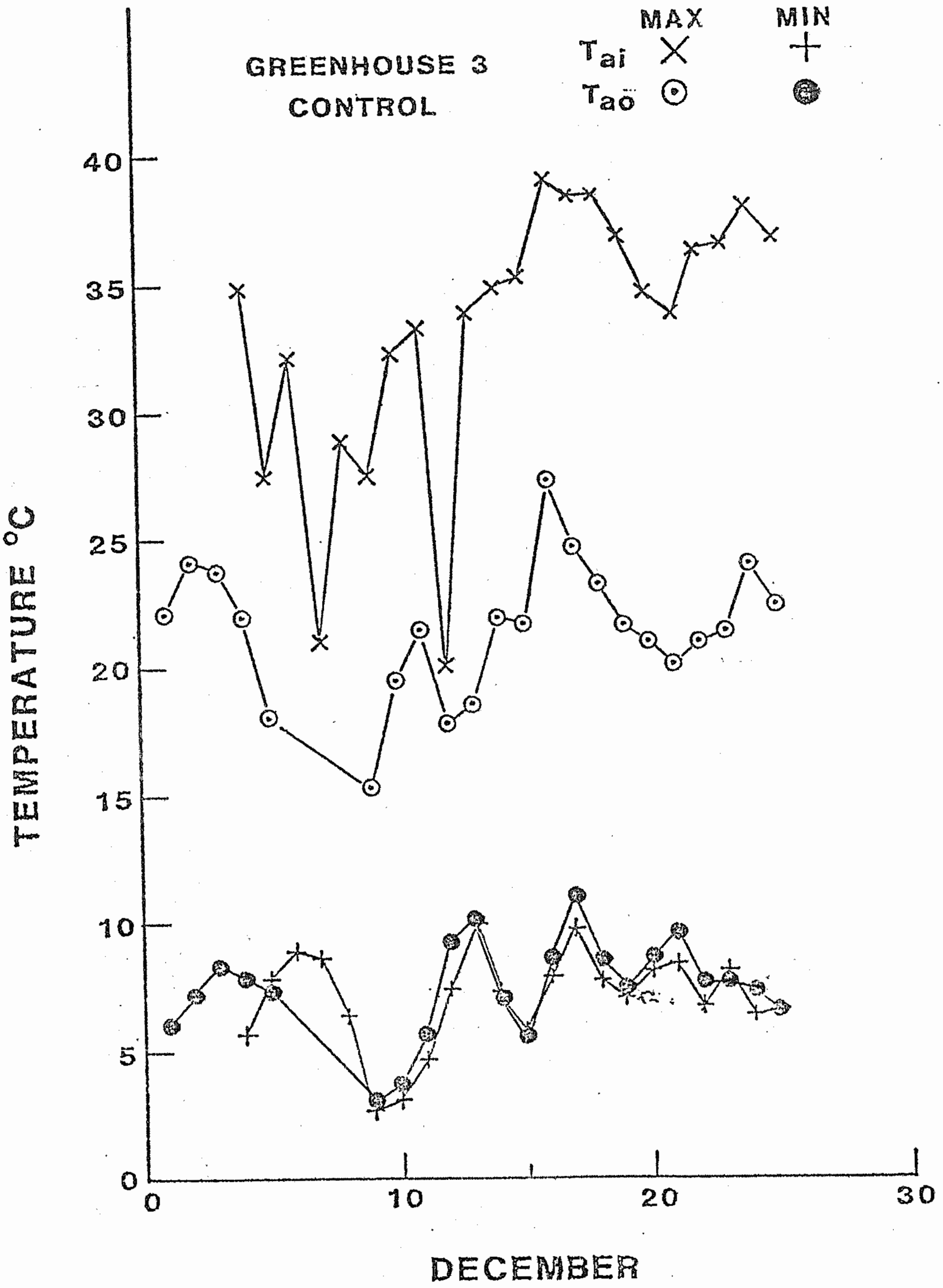

Figure 12. Maximum and minimum temperatures in unheated and uncooled control Greenhouse 3 in 1980.

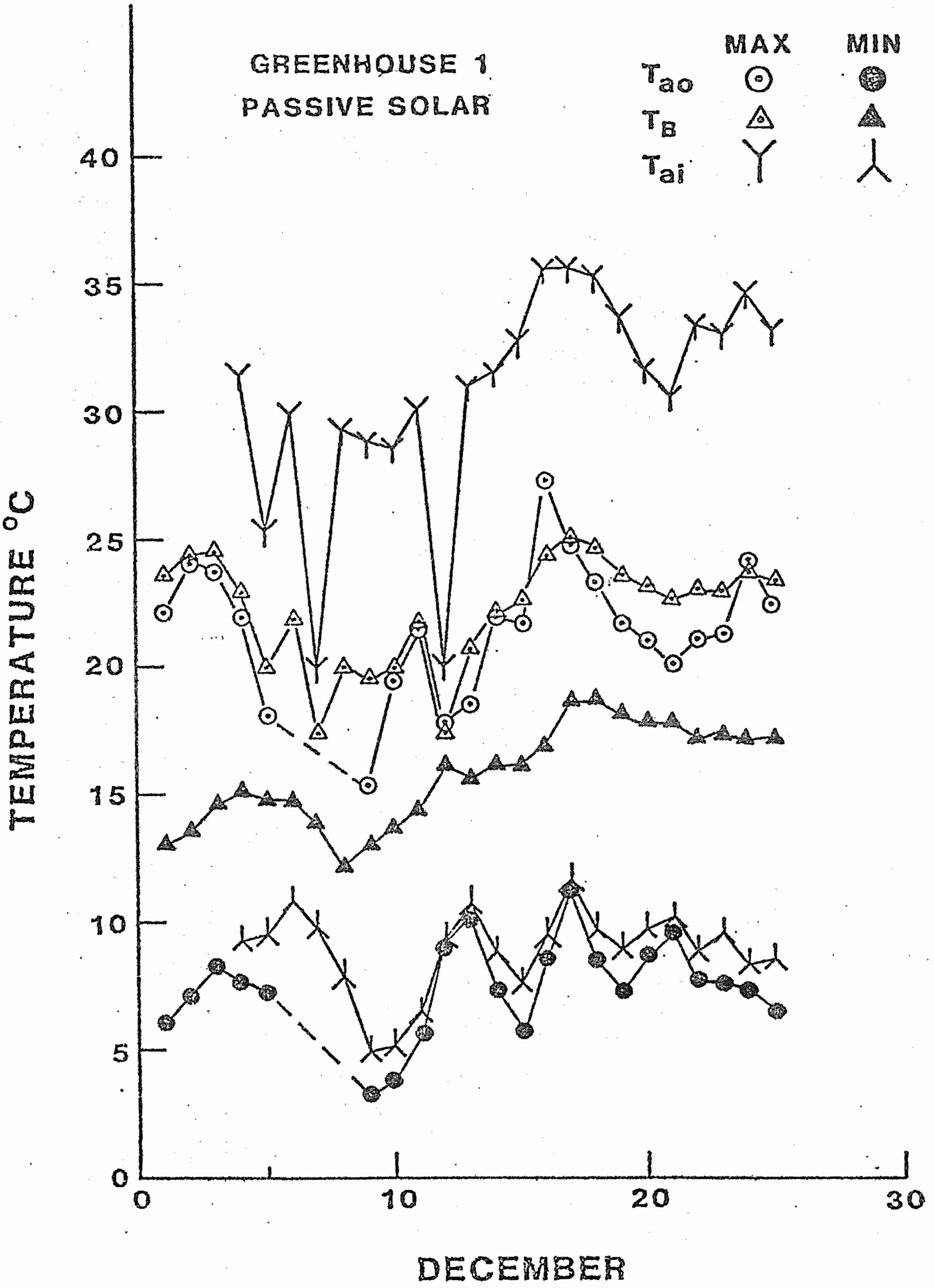

Figure 13. Maximum and minimum temperatures in passive solar Greenhouse 1 in 1980.

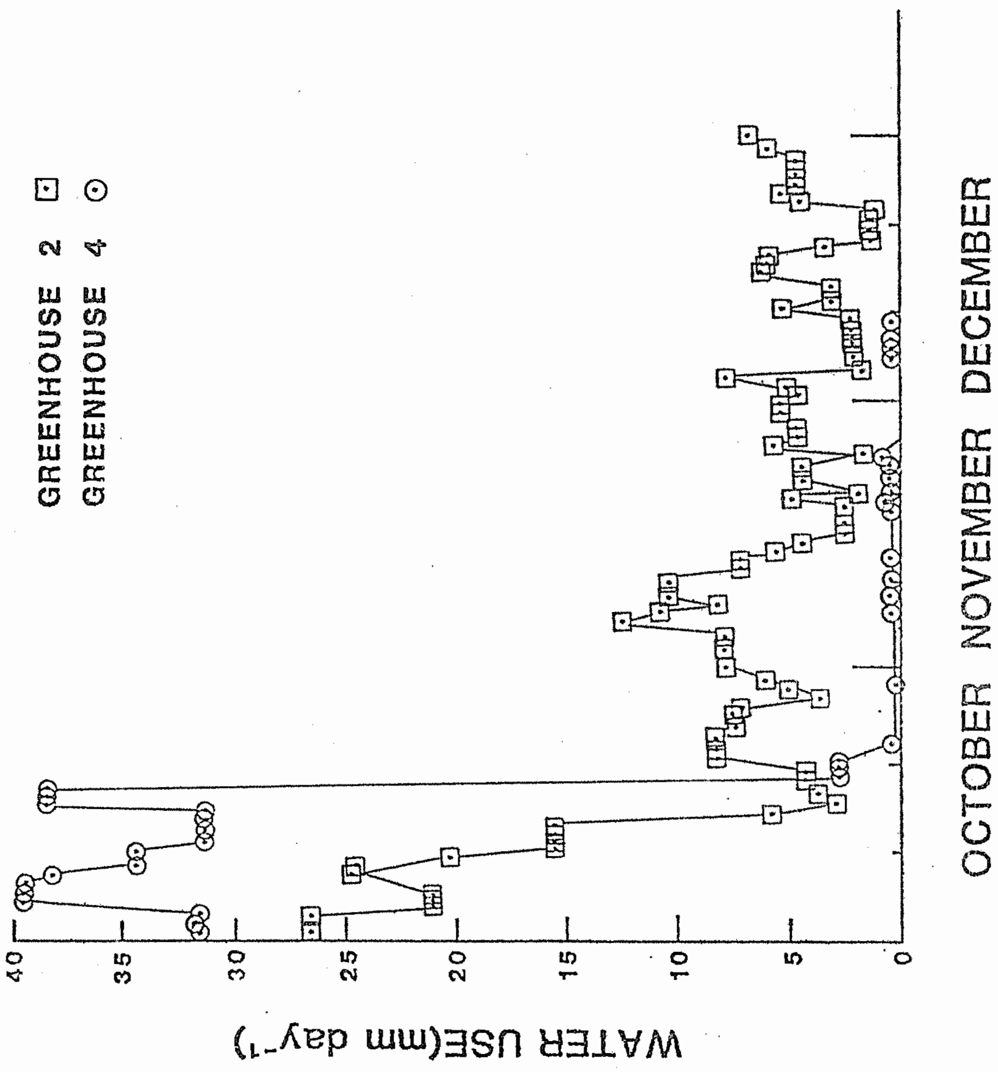

Figure 14. Daily water use by the evaporative cooler of conventional Greenhouse 2 and the cooling tower of unventilated, active solar Greenhouse 4.

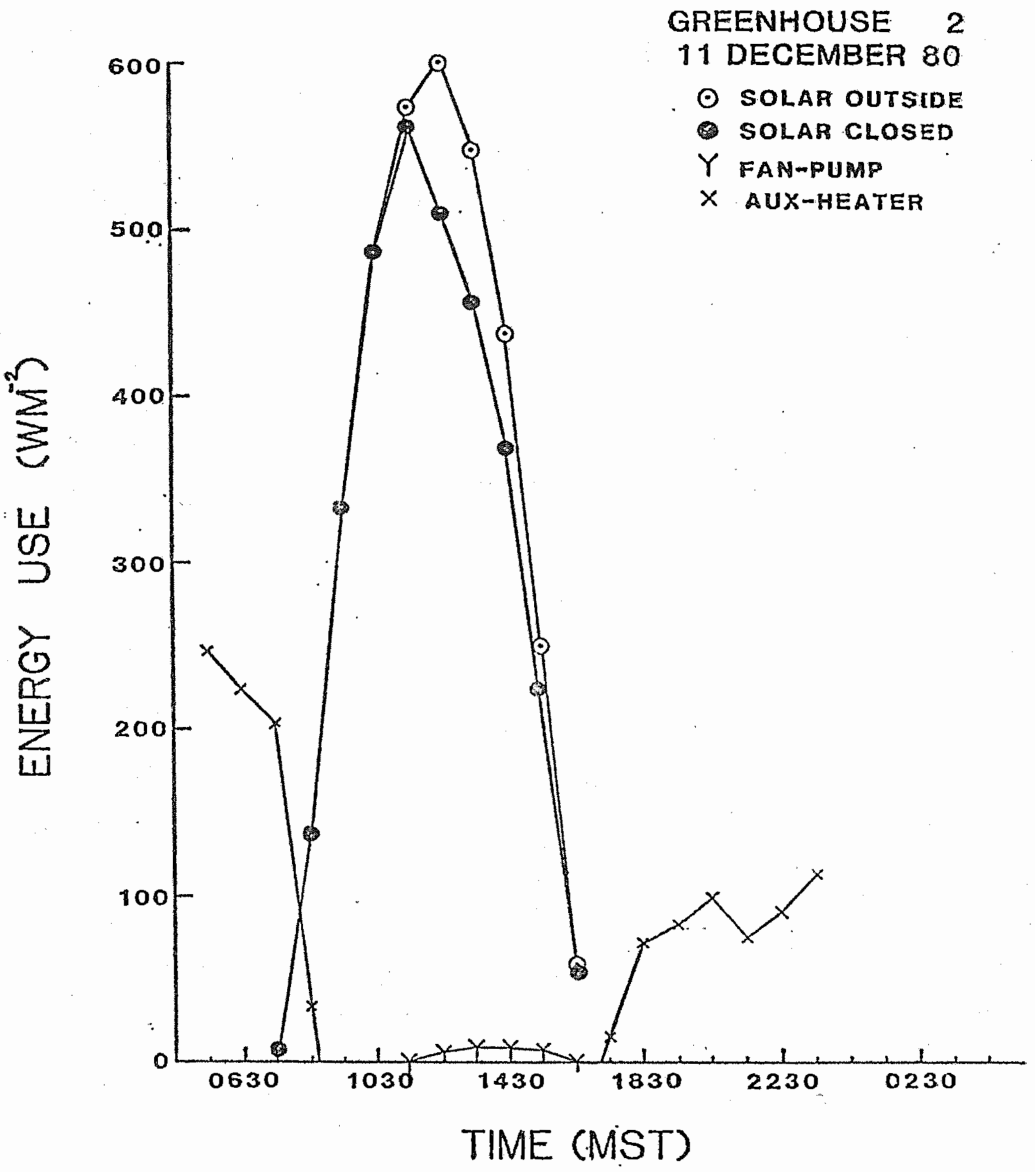

Figure 15. Energy use in conventional Greenhouse 2 on 11-12 December 1980. The solar closed points are the amounts of solar energy received while Greenhouse 2 was unventilated and could have been CO_2 enriched.

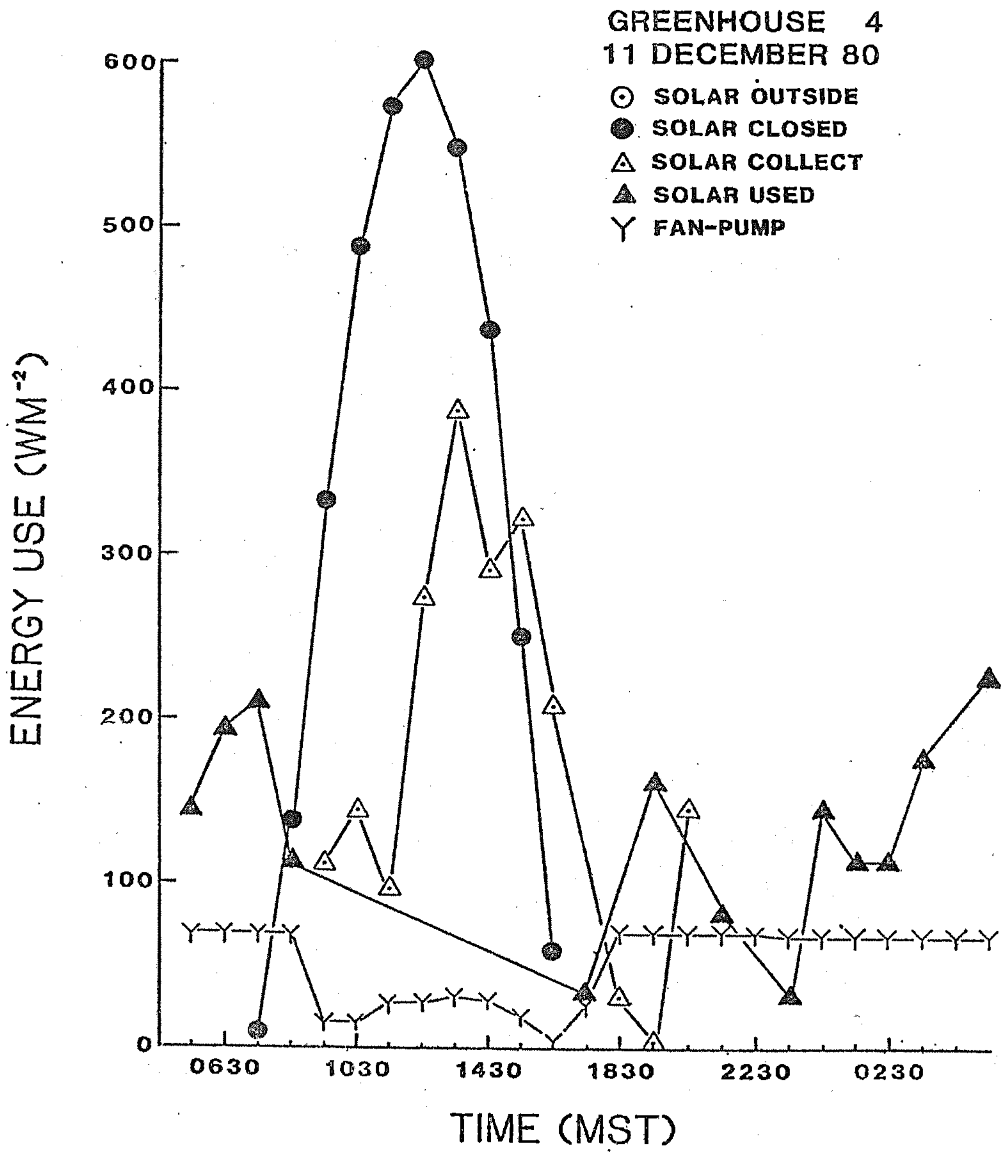

Figure 16. Energy use in active solar Greenhouse 4 on 11-12 December 1980. Greenhouse 4 did not require ventilation, so the solar outside points are superimposed on the solar closed points. Greenhouse 4 did not require any auxilliary heat.

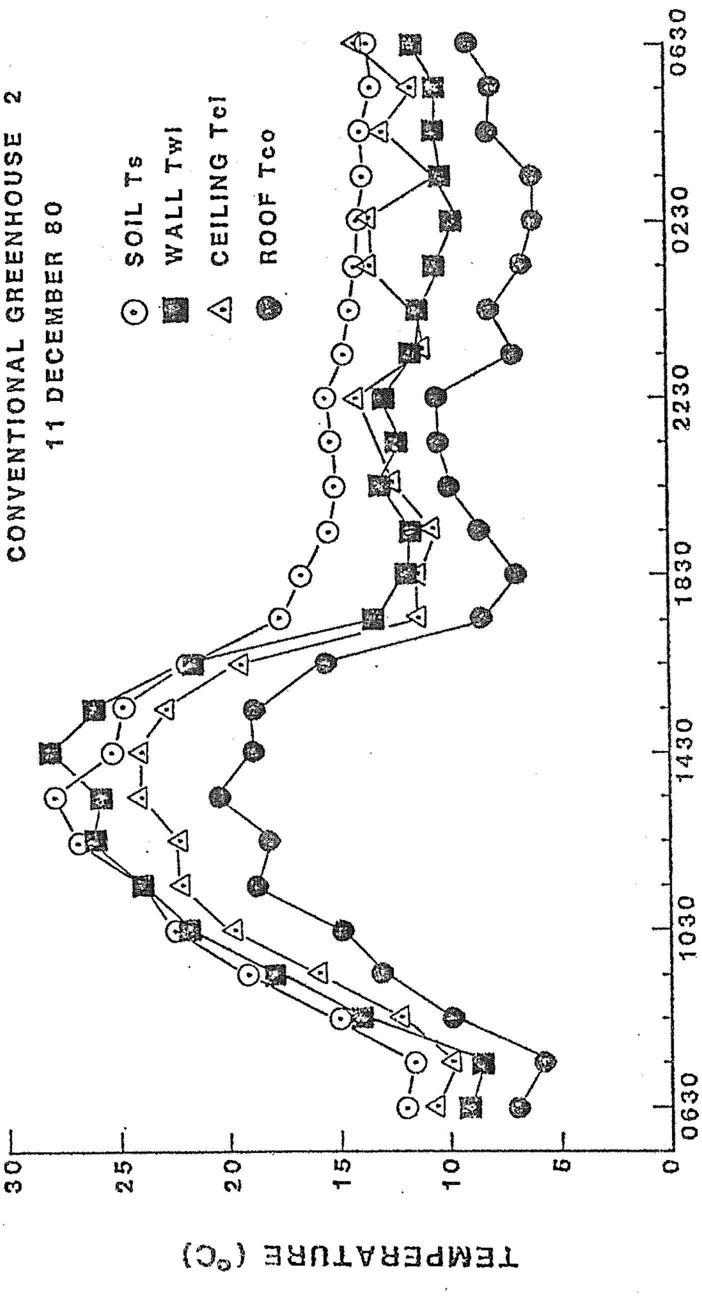

Figure 17. Soil, side wall, inside cover (ceiling), and outside cover (roof) temperatures in conventional Greenhouse 2 as measured by an infrared thermometer on 11-12 December 1980.

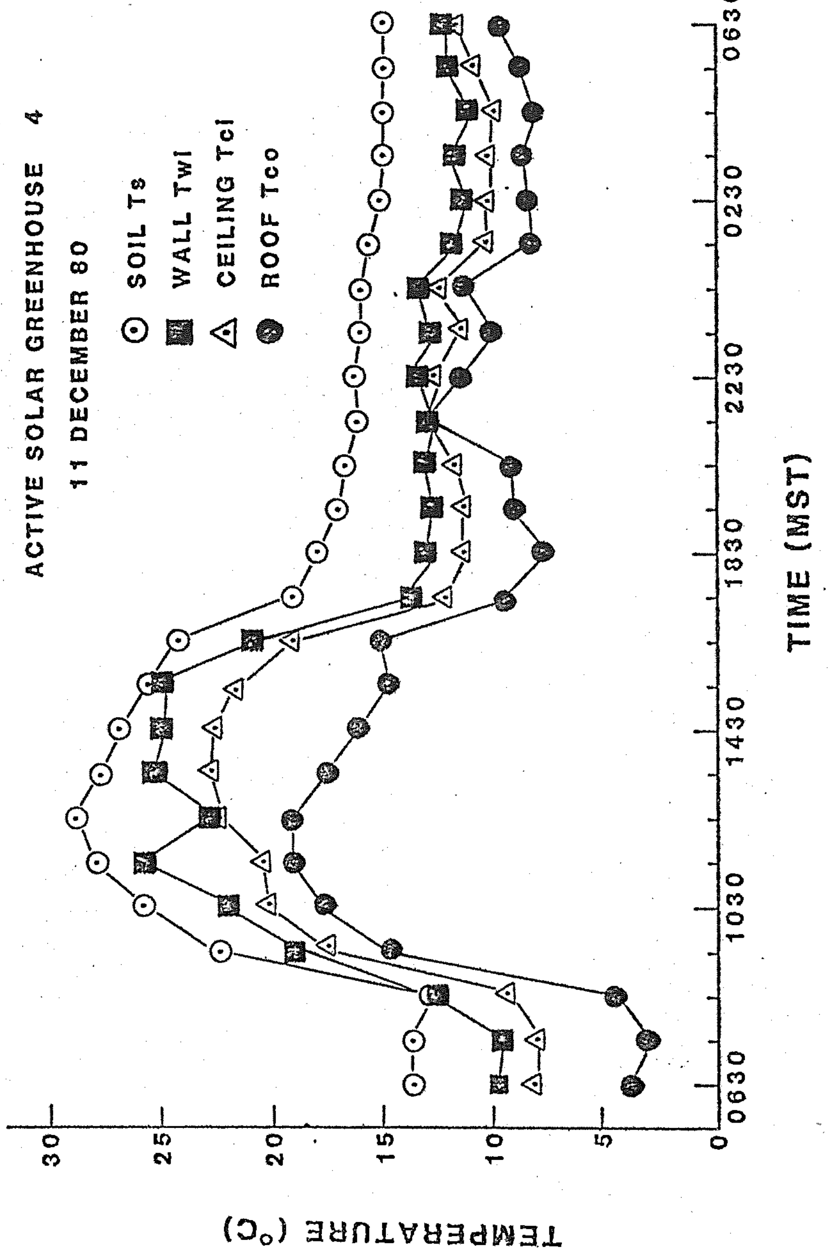

Figure 18. Soil, side wall, inside cover (ceiling), and outside cover (roof) temperatures in active solar Greenhouse 4 as measured by an infrared thermometer on 11-12 December 1980.

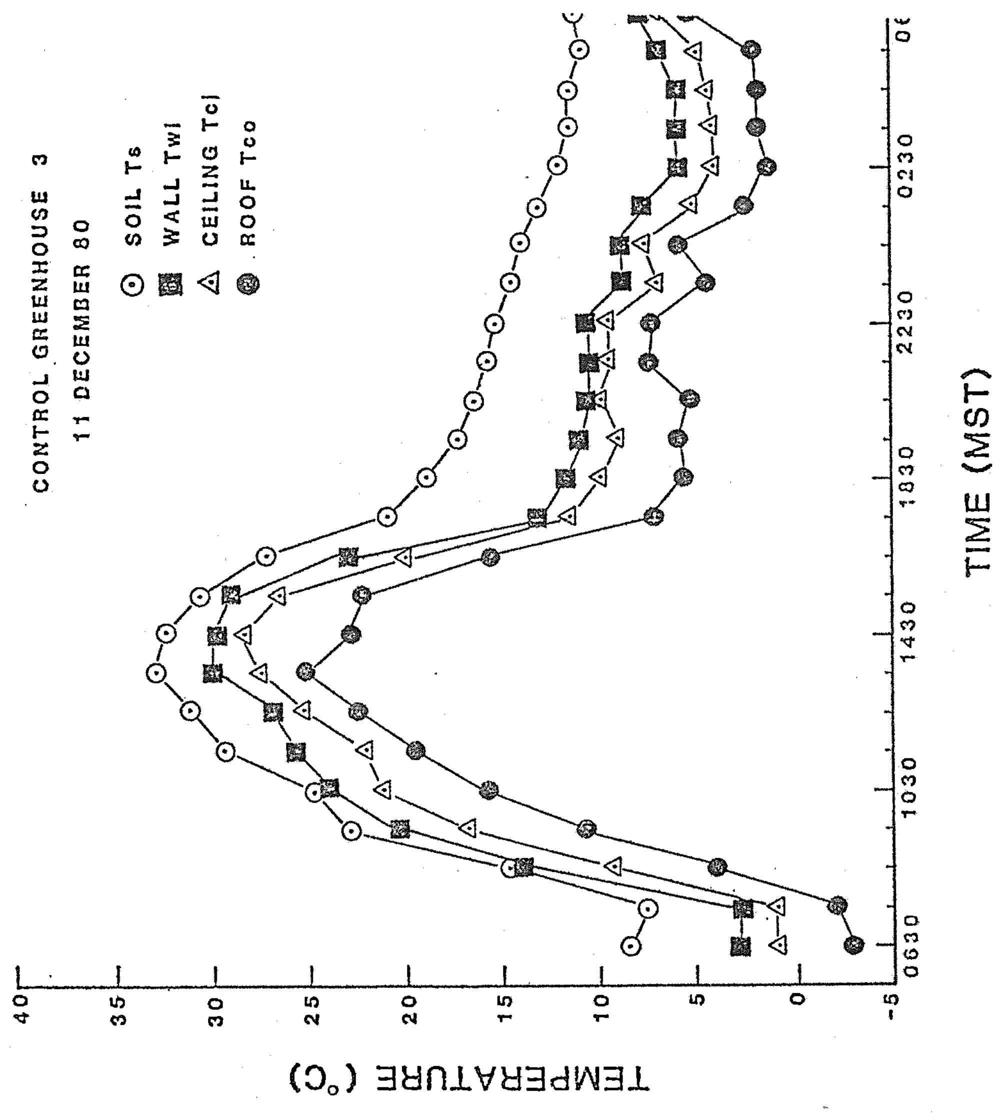

Figure 19. Soil, side wall, inside cover (ceiling), and outside cover (roof) temperatures in unheated and uncooled control Greenhouse 3 as measured by an infrared thermometer on 11-12 December 1980.

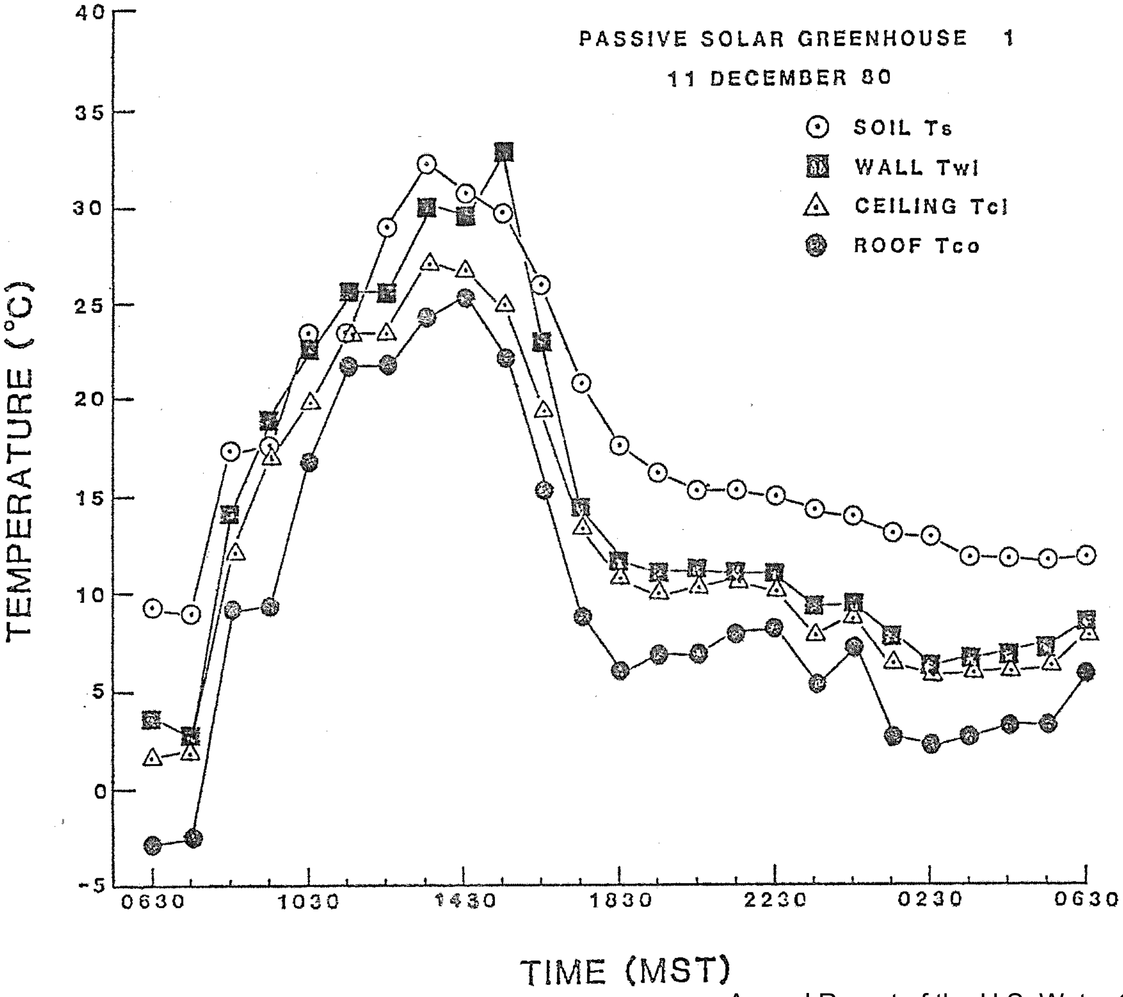

Figure 20. Soil, side wall, inside cover (ceiling), and outside cover (roof) temperatures in passive solar Greenhouse 1 as measured by an infrared thermometer on 11-12 December 1980.

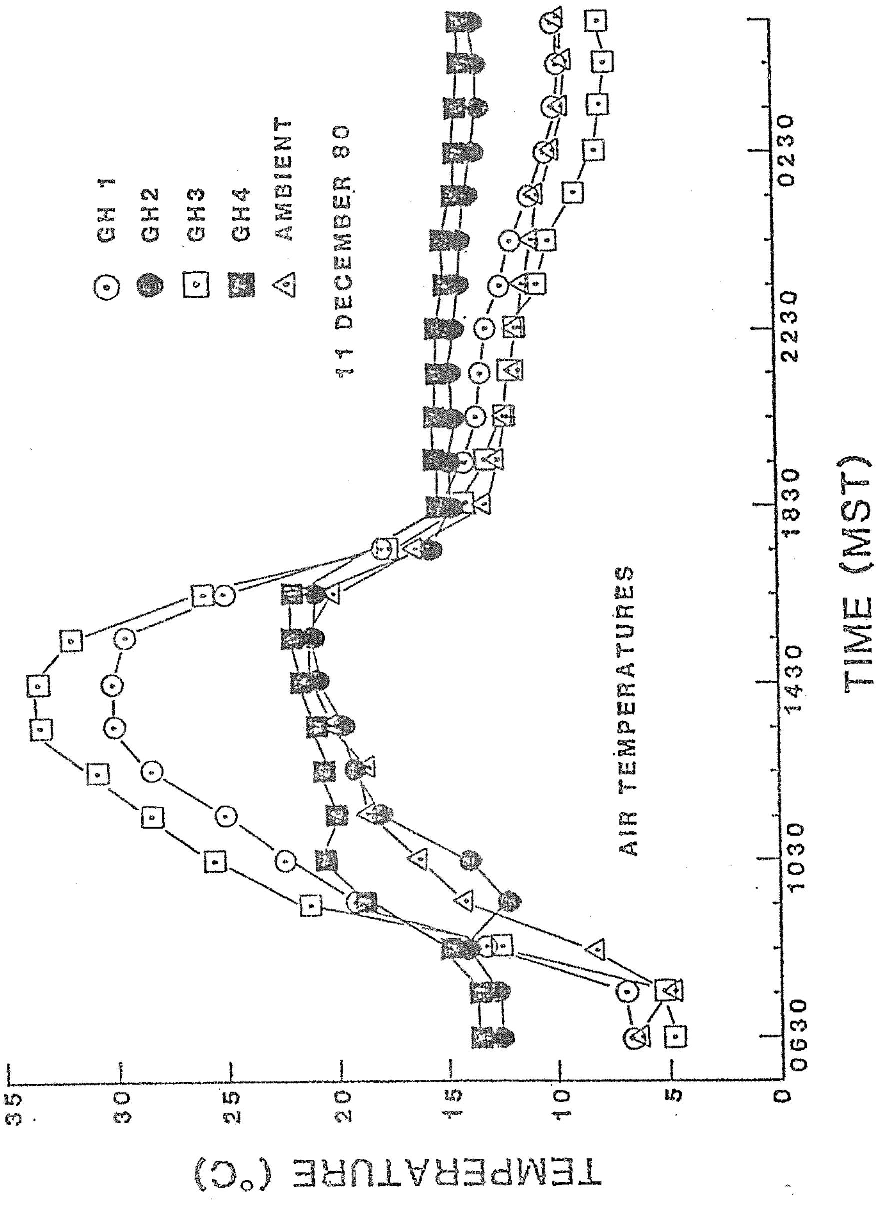

Figure 21. Air temperatures inside the four greenhouses and outside on 11-12 December 1980.

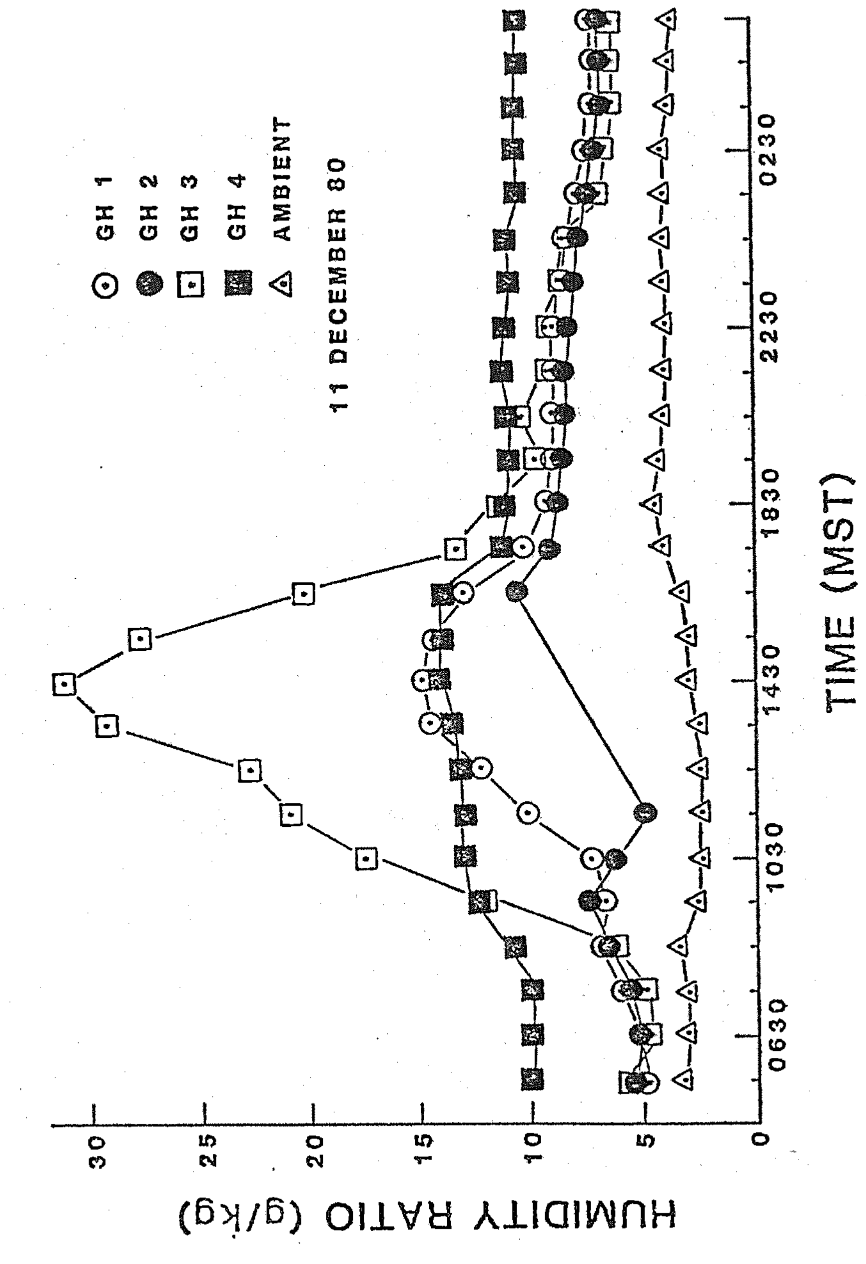

Figure 22. Air humidity ratios inside the four greenhouses and outside on 11-12 December 1980.

TITLE: MICROBIOLOGY OF SOIL AND WATER SYSTEMS FOR RENOVATION AND CONSERVATION OF WATER

NRP: 20790 CRIS Work Unit: 5510-20790-002

INTRODUCTION:

During 1980, the studies on biological aspects of nitrogen transformation and nitrogen removal from soil basins intermittently flooded with secondary sewage effluent were continued. This report summarizes the results obtained on nitrification-denitrification reactions in soil basins at the 23rd Avenue Project.

PROCEDURES:

The 23rd Avenue Project consisted of four large recharge soil basins (500 x 100 m) of about 10 acres that were intermittently flooded with secondary sewage effluent and dried, respectively, for nine days each. The water depth in the basins during flooding in both projects was about 20 cm. Soil samples were collected from each project only during the dry periods. Subsamples were extracted and analyzed, as soon as possible, for inorganic nitrogen components with an Automatic Technicon Analyzer. Other subsamples were prepared for measuring the rates of denitrification and moisture contents.

The acetylene inhibition method was used to quantitatively measure denitrification rates. The method blocks biological reduction of nitrous oxide to molecular nitrogen. Soil subsamples were placed in 40-ml septum vials and treated with about 90 µg NO_3-N/g, since nitrification was inhibited by acetylene (0.1 atm). Head space samples of 1.0 ml were obtained after incubation at 28 C for 24 hours and were analyzed for nitrous oxide with a gas chromatograph equipped with a thermal conductivity detector. Control soil samples without nitrate-N additions were also analyzed. The atmosphere in the vials was either helium or air with about 0.1 atm of acetylene.

RESULTS AND DISCUSSION:

The nitrogen transformation in the soil basins flooded with secondary effluent showed a natural and expected conversion of ammonium-N to nitrified-N (Table 1). The nitrification rates in the summer were about twice those during the winter. Soil environments during the winter promoted higher denitrification rates throughout the dry period. The higher summer temperature (35-40 C) and faster drying conditions rapidly created an oxidized environment unfavorable for denitrification in the surface of the soil basins, but the oxidizing metabolic activity of nitrifying bacteria was enhanced. During drying, nitrogen removals by denitrification of 21 percent in the winter and only 9 percent in the summer accounted for only a portion of the calculated total nitrogen removal of 60 percent, obtained during flooding and drying cycles.

Denitrification rates were greatest during the first two to three days of drying regardless of the season of the year. Soils treated with helium plus nitrate-N had the greatest rates of denitrification, followed by soils treated with air plus nitrate and air only, respectively. The additions of nitrate-N increased denitrification for only two to three days in soils treated with air. On the first day of drying, the low rates of denitrification in soil treated with air only resulted from the low amount of nitrified-N in the soil sample and the inhibition of nitrification by acetylene. With nitrification inhibited, denitrification could not occur, so nitrate-N was added to soils treated with air and helium. The nitrate-N treatments were the most accurate estimates of denitrification rates during drying in the surface soil (0-5 cm) of an undisturbed soil basin. These results have indicated that conditions necessary for maximum denitrification are present in the surface of the soil basins for only 48 to 72 hours at the start of the dry period during either summer or winter. The most important factors limiting denitrification were the rates of nitrification that controlled the concentration of nitrite-N and/or nitrate-N and the amount of the available organic carbon. The denitrification rates during drying in the surface 5 cm of soil accounted for only about 25 percent of the calculated total nitrogen removal of 60 percent. Thus, during intermittent flooding and drying cycles higher rates of denitrification nearer the soil surface during drying and environments favorable for nitrification-denitrification reactions during flooding provided additional nitrogen removal from the soil recharge basins.

In conclusion, management practices for maximizing denitrification in the surface soil, in terms of percent N-removal, must either decrease the nitrogen applied, enhance the environment favorable for nitrification-denitrification reaction, increase the numbers of physiologically active denitrifying bacteria or any combination of these practices. First, decrease the nitrogen applied by lowering the hydraulic head to attain infiltration rates of 15 cm/day or less. The N-removal should increase to an estimated 60 to 80%. In effect the rates of denitrification were not changed, only the relative amount of nitrogen applied. Second, enhance the environment favorable for nitrification-denitrification reaction during drying by maintaining the soil surface near saturation with intermittent daily sprinkler or slug flow application of small quantities of sewage effluent. This would result in little nitrate movement and induce extended activity of denitrification in reduced microsites. Third, increase the numbers physiologically active denitrifying bacteria in the surface soil by timely additions of organic carbon to support their growth and denitrifying activity. The denitrifying population must be physiologically active to provide a denitrification rate rapid enough for complete N-removal. Additions of organic carbon could be applied to the soil surface in the sewage effluent during the last 2 days of flooding and/or in application of sewage effluent during drying. Last, combination of the above practices would be necessary to maintain N-removals of 60 to 80% at infiltration rates of 20 to 60 cm/day.

SUMMARY AND CONCLUSIONS:

During 1980, the studies on biological aspects of nitrogen transformations and nitrogen removal from soil basins intermittently flooded with secondary sewage effluent were continued. Denitrification rates were measured in field soils with the acetylene inhibition method. The influence of flooding and drying cycles on the rate and duration of denitrification in soil basins at the 23rd Avenue Project were investigated in detail.

During drying, the nitrogen transformation in the surface 5 cm of soil basins previously flooded with secondary effluent showed a natural and expected conversion of ammonium-N to nitrified-N. Nitrification rates in the summer were about twice those during the winter, because of the higher summer temperatures that enhanced the oxidizing metabolic activity of nitrifying bacteria. Denitrification rates were greatest during the first two to three days of drying regardless of the season of the year. Soil environments during the winter promoted higher denitrification rates throughout the dry period. The higher summer temperature (35-40 C) and faster drying conditions rapidly created an oxidized environment unfavorable for denitrification in the surface soil of the basins. During 10 days drying denitrification accounted for 21 and 9 percent nitrogen removal in winter and summer, respectively. These percent N-removals accounted for only a portion of the calculated total N-removal of 60%. However, higher denitrification rates nearer the soil surface (1 to 2 cm) and environments favorable for denitrification while flooding would provide additional N-removal during intermittent flooding and drying cycles. Therefore, management practices for maximizing denitrification in the surface soil, in terms of percent N-removal, must either decrease the nitrogen applied, enhance the environment favorable for nitrification-denitrification reaction, increase the numbers of physiologically active denitrifying bacteria or any combination of these practices.

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Bouwer, H., Rice, R. C., Lance, J. C., and Gilbert, R. G. Rapid-infiltration system for wastewater renovation and beneficial reuse, 23rd Avenue Project, Phoenix, AZ. Final Report of cooperative project between City of Phoenix, and U. S. Water Conservation Laboratory, EPA Project S-802435-01 and 01. In preparation.

PERSONNEL: R. G. Gilbert and J. B. Miller

Table 1. Nitrogen transformation and denitrification rates in soil basins intermittently flooded with secondary sewage effluent from 23rd Avenue Treatment Plant.1/

Days Dry	Soil Nitrogen 2/ Ammonium-N		Nitrified-N	Denitrification rates 3/ He + NO_3-N	Air + NO_3-N	Air (Only)	Water Content
	(μgN/g)			(μgN_2O-N evolved/g/day)			(%)
			Winter:	Oct - Nov - Dec 1979			
1	110	(111)	1	63	19	<1	24.0
2	91	(127)	28	58	23	11	21.9
3	64	(121)	57	78	9	8	15.6
7	33	(155)	122	74	8	5	11.8
10	47	(198)	151	96	11	8	9.8
			Summer:	Jul - Aug - Sep 1980			
1	170	(176)	6	23	23	<1	29.6
2	81	(128)	47	33	14	7	21.4
3	45	(147)	102	25	4	3	18.0
7	28	(186)	158	15	2	1	8.6
10	20	(208)	188	16	1	1	6.8

1/ Results are data averaged from 3 and 5 dry periods during winter and summer, respectively.

2/ Soil samples were collected, extracted and analyzed as soon as possible for NH_4-N, NO_2-N and NO_3-N. Nitrified-N was the $\mu gNO_2\&NO_3$-N/g. The parentheses indicate the total inorganic nitrogen.

3/ Denitrification rates were measured in soil samples collected during dry periods with the acetylene inhibition method. Soil samples were incubated for 24 hours in flasks containing helium or air and 0.1 atm of acetylene. Nitrate N additions were equivalent to 91 μgNO_3-N/g of soil.

TITLE: WASTEWATER RENOVATION BY SPREADING TREATED SEWAGE FOR GROUNDWATER RECHARGE

NRP: 20790 CRIS WORK UNIT: 5510-20790-003

INTRODUCTION:

The work at the 23rd Avenue rapid-infiltration system was continued in 1980 to study the effect of the lower algae content in the secondary effluent entering the infiltration basins (due to construction of a bypass canal in 1979) on infiltration rates, to determine the effect of breaking up the surface soil in the basins on infiltration rate, to determine the response of the groundwater table to recharge, and to evaluate the quality of the renovated water in relation to that of the secondary effluent. The latter not only consisted of the routine parameters like nitrogen, phosphorus, organic carbon, salts, suspended solids, and fecal coliforms, but also of viruses (in cooperation with Baylor College of Medicine) and trace organics (with Rice University and Stanford University).

The 23rd Avenue Treatment Plant started to chlorinate its effluent in the middle of November. This was a good opportunity to study the effect of chlorination on the type and concentration of trace organics in the effluent and in the renovated water pumped from below the infiltration basins. Accordingly, a cooperative study with Stanford University was initiated. The first phase of this study (pre-chlorination conditions) was completed in the fall of 1980. The second phase (post-chlorination conditions) will be done in the spring of 1981.

The wastewater renovation work is nearing completion and its scope will be significantly reduced after the summer of 1981. Most of the effort of the Subsurface Water Management Group will then be directed toward the effect of irrigated agriculture on recharge and quality of the underlying groundwater, including transport of water and chemicals in the vadose zone. To get some insight of vadose zone conditions in irrigated desert valleys, soil samples were obtained when storm-runoff injection wells were drilled in the Salt River Valley. The soil samples were analyzed for particle size distribution, water content, and chemical composition of the water.

I. 23RD AVENUE PROJECT

1. INFILTRATION RATES

Infiltration rates in 1980 started out on the order of 0.3 m/day in January and February, using a schedule of one week flooding and three weeks drying (Figures 1, 2, 3, and 4). During March and the first half of April, the project was dry to allow cleaning of the bypass channel which had become clogged with tumbleweeds. Burning was not very effective, so that the tumbleweeds had to be removed with a grade-all.

After the long dry-up, flooding and drying periods were set at two weeks each and infiltration rates were higher than before, but the average was mostly below 0.5 m/day. This was still below the anticipated rate for the surface "soils" in the basins, indicating that surface clogging or crusting still persisted (possibly residual cementing by $CaCO_3$ deposits due to the algae-laden effluent in 1975 and 1976). To break up the surface layer, the soil in the basins was ripped with a road grader. Disking or cultivating was not possible because of the many large rocks and boulders in and on the soil. The ripping teeth on the grader were mounted about 20 cm apart and penetrated the soil about 10 cm. Following this operation, which took place in June for basins 2 and 3 and in July for basins 1 and 4, infiltration rates were so high that first only one basin could be flooded at a time with the flow from the bypass channel. Even then, the inflow was not sufficient to cover the entire basin and infiltration rates had to be calculated on the basis of the estimated flooded area. In September 1980, the basins could be operated again in pairs and flooding and drying periods again were two weeks each. The average infiltration rates now were on the order of 1 m/day, except for basin 4, where they were about 0.5 m/day in August-September-October, and about 0.25 m/day in November-December. The increase in infiltration rate is reflected in the steeper slope of the accumulated infiltration curves after July (Figure 5). Hydraulic loading rates for the entire year were 107 m for basin 1, 83 m for basin 2, 87 m for basin 3, and 49 m for basin 4.

The average hydraulic loading of the four basins was 82 m for the entire year. Of this amount, however, 21 m or only 25% infiltrated in the first six months of the year. Assuming that annual ripping would produce average hydraulic loading rates of 100 m/year, the increase due to the ripping is about 40 m/year (based on previous hydraulic loadings of 60 m/year). The cost of ripping the four basins was $870. Thus, the cost of the increased capacity is 870/(40x16x10000) = $0.00014 per m^3 or $0.14 per 1000 m^3 ($0.18 per acrefoot). This indeed is an inexpensive way of increasing the capacity of the system, considering that the total cost of putting the effluent into the ground and pumping it up as renovated water is on the order of $10 per 1000 m^3 or acrefoot.

The infiltration data indicated that the design hydraulic loading rate can be conservatively estimated at 90 m/yr. This would give the 16-ha rapid-infiltration system a capacity of 14.4 million m^3 per year (12,000 acre feet/year) or almost 40,000 m^3/day (32 acre feet/day, 11 mgd, or 7600 gpm). Additional hydraulic loading can probably be obtained by increasing the water depth in the infiltration basins in the winter. Due to the lower temperatures and reduced sunlight intensity, algal blooms would then be unlikely and the larger depths could increase infiltration rates. Small water depths should be maintained in the rest of the year, however. To pump renovated water from the aquifer at the design hydraulic loading rate would require three wells on the center dike (including, and similar to, the Center Well already installed). The additional wells should be somewhat deeper than the Center Well (100 m, for example) to maintain sufficient capacity when groundwater levels are low.

A hydraulic loading rate of 90 m per year would be about 14% of the average vertical hydraulic conductivity of the soil in the basins, assuming that the infiltration rate of approximately 1.8 m/day obtained when the basins were first flooded and the effluent advanced as sheet flow over the soil was a reasonable reflection of the vertical hydraulic conductivity of the upper soil layers.

The design hydraulic loading rate of 90 m per year is about four times higher than the rate of 22 m per year obtained in the period 1975-1976. The difference, of course, is due to the greatly reduced suspended solids (algae) content of the effluent going into the infiltration basins following the completion of the bypass channel. The suspended solids content of the effluent entering the infiltration basins through the bypass channel generally was below 10 mg/ℓ, and that of the effluent leaving the basins was often even lower. This is much less than the suspended solids contents of the basin inflows before construction of the bypass channel, which were on the order of 10 to 20 mg/ℓ in the winter and 50 to 100 mg/ℓ in the summer. Algae still grew in the infiltration basins, but they were more of the types that grow on the bottom or float on the surface, rather than the uni-cellular, suspended algae that previously gave the water such a green appearance. Thus, the effluent water itself in the infiltration basins remained quite clear.

2. GROUNDWATER LEVELS

The general slope of the groundwater table to the north continued in 1980, as evidenced by the water levels in the South, Center, and North Wells (Figure 6). The rise of these water levels in January and February 1980 was due to recharge from the Salt River, which for the third year in succession was flowing for the first few months of the year, this time at rates from 50 to 50,000 m^3/sec. The decline of the groundwater levels from March to August 1980 was due to dissipation of the groundwater mound caused by recharge from the Salt River and to groundwater pumping from irrigation wells north of the project. In August, groundwater levels began to rise again, probably because of increased infiltration rates in the basins (see Figures 1, 2, 3, and 4) and of decreased groundwater pumping for irrigation. The curves in Figure 6 indicate that the depth of the groundwater table below the bottom of the recharge basins varied from a minimum of about 3 m on the south side of the project at the end of February to a maximum of about 13 m on the north side of the project in October.

Groundwater levels in the 18, 24, and 30-m Wells in the center of the project were very similar (Figure 7). As could be expected, the groundwater levels in the 18-m Well were highest, and also above the water levels in the Center Well, which is perforated from 30 to 55 m and gives the average hydraulic head for that depth range. These differences are due to downward flow components in the center of the recharge flow system in the aquifer.

Temporary peaks or rises in the groundwater levels of Figures 6 and 7 are correlated with flooding periods for nearby basins (basin 1 for North Well, basins 2 and 3 for Center Well and 18-, 24-, and 30-m Wells, and basin 4 for South Well). The rise in April 1980 of the water level in the 18-m Well was used to calculate the transmissivity of the aquifer from groundwater recharge theory (see second paragraph below).

Selected profiles of groundwater levels across the infiltration basins from south to north are shown in Figure 8. The predominant groundwater movement again was from south to north, except for the profiles on 18 August, 15 September, 13 December, and, to a lesser degree, 11 July. These four profiles all are associated with flooding of basins 2 and 3. Since these basins are in the center and the infiltration rates were high following the ripping of the surface soil in July, the water table in the center rose high enough to form a typical groundwater mound with lateral flow in both directions away from the center.

An estimate of aquifer transmissivity was obtained from the rise of the groundwater mound below the infiltration basins. Figure 7 shows that the water level in the 18-m Well rose 1 m in ten days in the second half of April 1980, due to flooding of basins 2 and 3. The average infiltration rate for the two basins during that period was 0.33 m/day (Figures 2 and 3). Assuming that the fillable porosity of the wetted vadose zone was 0.05, this yielded $1/(0.33 \times 10/0.05) = 0.015$ for the parameter on the ordinate of Bianchi and Muckel's dimensionless graph for mound rise below rectangular recharge basins (Figure 8.21 in Bouwer, Groundwater Hydrology, McGraw-Hill, 1978). The length-to-width ratio L/W for the flooded area of basins 2 and 3 was $465/188 = 2.5$, so that the corresponding abscissa parameter could be read from Bianchi and Muckel's graph as about 0.023 (assuming linearity of the curves near the origin), from which T was calculated as 84,000 m^2/day. This value was between the 14,600 m^2/day obtained with the slug test in 1975, and the 100,000 m^2/day obtained with the Theis pumping test in 1979 (both on the Center Well).

The difference between the T-values from the various tests is undoubtedly due to the methodology, particularly as it affects the portion of the aquifer involved in the flow system and the direction and distribution of the flow therein. For purposes of design and prediction of groundwater mound behavior in the area, a T-value of 50,000 m^2/day and a fillable porosity or storage coefficient of 0.05 may be reasonable and probably will be on the conservative side.

3. SUSPENDED SOLIDS

In 1980, the suspended solids content of the sewage effluent entering the infiltration basins generally was in the range of 5 to 25 mg/ℓ,

TABLE 2. REFRACTORY VOLATILE ORGANICS ($\mu g\text{-}l^{-1}$): 23RD AVE. PROJECT, PHOENIX, ARIZONA

	Compound	Purity index	GC Conf.	Sewage		Renovated water from 18-m Well				
				102	111	100	103	106	109	113
1.	Trichlorethylene	947		.032	.038					
2.	Toluene	958	x	.964	1.310	.017	.009	.008	.019	.024
3.	Tetrachloroethylene	979	x	.251	.050	.029	.021	.034	.065	.074
4.	2,4-Dimethyl-3-hexanol	684		.011	<.008	.007	.005	.004	.006	.007
5.	Chlorobenzene	764	x	.015	<.008	P*	.002	.002	.002	.002
6.	1,3,5,7-Cyclooctatetraene	933				.030	.007	.008	.015	P
7.	p-Xylene	968	x	2.140	4.050	.049	.010	.040	.011	.019
8.	o-Xylene	960	x	.210	.168					
9.	Diethyldisulfide	979		.015	.036					
10.	Propylbenzene	824	x	.056	.021					
11.	m-Ethyltoluene	881	x	.234	.129					
12.	o-Ethyltoluene	924	x	.105	.049					
13.	1,3,5-Trimethylbenzene	908	x	.132	.047					
14.	1,2,3-Trimethylbenzene	945	x	.128	.085					
15.	2,4,4-Trimethylbenzene	913	x	.332	.129	P				
16.	m-Dichlorobenzene	947	x	.263	<.008	P				
17.	p-Dichlorobenzene	943	x	.617	.355	.042	.022	.043	.072	.069
18.	o-Dichlorobenzene	945	x	.986	.210					
19.	1-Methyl-4-isopropyl-7-Oxabicyclo-[2,2,1]-heptane	808		.128	.085					
20.	1-Chloro-2,3-dihydro-1H-indene	927				.025	.017	.040	.080	.070
21.	1,1'-Bicyclopentyl	910		.008	.080					
22.	2-Ethyl-1,4-dimethylbenzene	915		.008	.080					
23.	1-Methyl-2-isopropylbenzene	770	x	.008	.080					
24.	1-Methyl-4-isopropylbenzene	734	x	.086	.132					
25.	Fenchone	706	x	.075	.056					
26.	m- or p- Cresol	881	x	.075	.078					
27.	1,2,3,4-Tetrahydronaphthalene	773		1.490	1.980					
28.	Camphor	582	x	.164	<.008					

(continued)

and averaged 13.4 mg/ℓ (Figure 9). Thus, the bypass channel continued to be effective in minimizing the algae growth and suspended solids content of the effluent entering the infiltration basins. The suspended solids content of the renovated water averaged 1.2 mg/ℓ for the Center Well. Individual concentrations did not exceed a value of 5 mg/ℓ (Figure 9). The same was true for the 18-m Well (Figure 10), where the average suspended solids content in 1980 was 1.9 mg/ℓ.

4. DISSOLVED SOLIDS

In 1980, the TDS content of the sewage effluent ranged between 600 and 800 mg/ℓ (Figure 11), and averaged 742 mg/ℓ. Average TDS concentrations of the renovated water in 1980 were 784 mg/ℓ for the Center Well, 795 mg/ℓ for the 18-m Well, and 779 mg/ℓ for the North Well. At a loading rate of 100 m/year and an evaporation of 1.8 m/year from the soil and water surface in the infiltration basins, evaporation would account for about 15 mg/ℓ of the 44 mg/ℓ average difference between the TDS content of sewage effluent and renovated water. The rest of the increase may be due to mobilization of calcium carbonate in the soil and aquifer as the pH of the effluent dropped from slightly alkaline (about 8) to neutral. Variations in TDS contents and different times of sampling may also have played a role.

5. pH VALUES

The secondary effluent was slightly alkaline (pH about 8) and the renovated water essentially neutral (pH about 7). Algae growth in the 32-ha pond caused pH values of the effluent to increase to 9 and sometimes even higher as CO_2 was taken up for photosynthesis during the day. After the bypass channel was constructed and used, however, algae growth in the effluent was much reduced and the pH of the effluent in the infiltration basins remained around 8.

6. NITROGEN

In 1980, the total-N content of the secondary sewage effluent entering the infiltration basins generally ranged between 15 and 25 mg/ℓ (Figure 12) with an average of 17.0 mg/ℓ, again mostly as NH_4-N (15.6 mg/ℓ). The organic-N content averaged 1.45 mg/ℓ, and the NO_3-N content 0.01 mg/ℓ. Renovated water from the North Well again showed several NO_3-N peaks (Figure 13). The peak on 10 May occurred 10 days after the 1 May beginning of a flooding period for basins 1 and 4. Since the average infiltration rate for basin 1 for that flooding period was 0.7 m/day (Figure 1), the arrival of the NO_3-peak was about three times slower than would have been expected from the arrival times and infiltration rates associated with the November and December nitrate peaks in 1979. This difference was probably due to the long dry period (about 2 months) preceding the 1-10 May flooding period, which gave adequate time for the water to drain from the vadose zone. Thus, when flooding was started on 1 May, the vadose zone was relatively dry and it took the wet front longer to reach the groundwater table.

Nitrate peaks were also observed in the renovated water from the 18-m Well (Figure 14). The peak in September occurred only a few days after the start of the September flooding periods for basins 2 and 3. This was due to the high infiltration rate in basins 2 and 3 after they were ripped (see Section 1). The NO_3-N concentration in the renovated water from the Center Well showed a decreasing trend (Figure 15) and averaged 5.2 mg/ℓ. NH_4-N concentrations continued to be close to zero (0.07 mg/ℓ average). Since the average total-N content of the secondary effluent was about 17.1 mg/ℓ (Figure 12), the nitrogen removal in the soil aquifer system in 1980 was 69%. Average concentrations of the various forms of nitrogen in the renovated water during 1980 were as follows (in mg/ℓ):

	North Well	Center Well	18-m Well
NO_2-N	0.013	0.007	0.024
NO_3-N	6.1	5.2	7.04
NH_4-N	0.47	0.07	1.85
Organic-N	0.12	0.015	0.22
Total-N	6.7	5.29	9.13

The highest concentration of organic N was observed in the 18-m Well which is in the center of the basin area and penetrates the aquifer the smallest distance. The studies on nitrate peaks and coliform peaks in the water from the 18-m Well have indicated that the effluent water moves very fast from the infiltration basin to the intake of the 18-m Well. Hence, "treatment" is reduced and the renovated water from the 18-m Well has more organic carbon, fecal coliforms, and other substances than that from the other wells.

7. PHOSPHORUS

In 1980, PO_4-P concentrations averaged 5.0 mg/ℓ for the secondary effluent, 2.77 mg/ℓ for the renovated water from the 18-m Well, 1.43 mg/ℓ for that from the North Well, and 0.42 mg/ℓ for that from the Center Well (Figure 16). The renovated-water curves in Figure 16 show the additional decrease of the PO_4-P concentration as the renovated water continues to travel laterally (as to the North Well, for example) or vertically (as to the Center Well). The curves for the renovated water also exhibited a gradually increasing trend, especially after June 1980 when infiltration rates in the basins were markedly increased due to ripping of the soil. Thus, PO_4-P removal in the soil-aquifer system also depended on the infiltration rate.

8. FECAL COLIFORM BACTERIA

In 1980, the average fecal coliform concentration of the sewage effluent entering the infiltration basins was 1.3×10^6/100 mℓ before chlorination, and 3.4×10^4/100 mℓ after 17 November when the effluent began to receive chlorination. Fecal coliform concentrations of the renovated water in 1980 were considerably higher than in previous years. Renovated water from the North Well had peak coliform concentrations of 43 and 45/100 mℓ (Figure 17), but the average concentration was 1.36/100 mℓ. The Center-Well water showed peak coliform concentrations of 140 and 160/100 mℓ and had an average concen-tration of 24/100 mℓ (Figure 18). Very high coliform peaks were observed in the renovated water from the 18-m Well in the center of the project (Figure 19), where peaks regularly exceeded values of 1000/100 mℓ and at one time shot up to 17,000/100 mℓ. The two highest peaks occurred in August and September, after the infiltration basins had been ripped to increase infiltration rates. The average fecal coliform concentration for the water from the 18-m Well was 1000/100 mℓ.

The average fecal coliform concentration of 24/100 mℓ for the "production" water from the Center Well was too high for unrestricted irrigation under the proposed new standards for effluent irrigation in Arizona (geometric mean not more than 2/100 mℓ and single sample not more than 25/100 mℓ). Lower fecal coliform concentrations could be obtained by flooding schedules that avoid simultaneous new flooding of basins 2 and 3. If basins 1 and 2 are flooded at the same time, and then basins 3 and 4 for the next flooding sequence, the center wells would never pump renovated water that infiltrated in the adjacent basins 2 and 3 at the same time. If, for example, basins 1 and 2 are filled, the initial infiltration from basin 2 would increase the fecal coliform concentration in the water from the Center Well. However, the well would also pump renovated water that infiltrated at the end of the flooding period from basin 3. Since this renovated water would have a low coliform content, it would reduce the fecal coliform concentration in the pumped water. Also, the 23rd Avenue Treatment Plant has started chlorinating its effluent in November 1980, which should reduce coliform concentrations in the effluent and the renovated water. This will be studied after the chlorination has been in effect for some time.

The higher fecal coliform concentrations in the renovated water in 1980 must have been caused by the higher infiltration rates resulting from the use of the bypass channel, and by the ripping of the surface soil in the infiltration basins. The high values in the renovated water from the 18-m Well must also have been due to the very fast arrival of renovated water at this well from the infiltration basins, as indicated by the short times between starts of new flooding periods in basin 2 and the appearance of nitrate and coliform peaks in the renovated water from the 18-m Well (Figures 14 and 19).

9. VIRUSES

Renovated water from various wells was sampled twice in 1980 for viruses, pumping 800 to 2000 ℓ of renovated water through special filters to concentrate the viruses in a small volume that could be sent to the laboratory for assay. In January 1980, viruses were concentrated into small samples by pumping well water through a fiberglass cartridge filter and injecting HCL to adjust the pH of the well water to 3.5 and $AlCl_3$ to a concentration of 0.0005 $MAlCl_3$ before the well water entered the filter (Gilbert et al., 1976). The adsorbed viruses were eluted from the filters with glycine buffer (pH 11.5) and the eluate was neutralized, frozen, and shipped to C. P. Gerba of the Baylor College of Medicine, Houston, Texas, for analysis. In June 1980, samples were concentrated by simply pumping well water through recently developed positively charged filters. The filters were packed in ice and shipped to Baylor College of Medicine where the viruses were eluted and assayed. Duplicate samples were obtained in all cases. Average virus concentrations are shown in Table 1.

An average of about 0.15 PFU/100 ℓ were detected on the January sampling date while about 1 PFU/100 ℓ was found in June (Table 1). All of the virus concentrations were well below the 1 PFU/40 ℓ limit proposed by the Arizona Department of Health Services for wastewater to be used for unrestricted irrigation. The differences in virus concentrations for the two sampling dates could have been due to differences in the concentration techniques, to seasonal variation in the virus concentrations in the sewage, or to differences in virus survival times in the soil during winter and summer.

10. TOTAL ORGANIC CARBON

Total organic carbon (TOC) concentrations in the secondary effluent and renovated water from various wells in 1980 are shown in Figures 20, 21, and 22. The average values were 9.34 mg/ℓ for the secondary effluent, 2.45 mg/ℓ for the renovated water from the North Well, 1.86 mg/ℓ for that from the Center Well, and 3.17 mg/ℓ for that from the 18-m Well. The 18-m Well, which is next to basin 2 and penetrates the groundwater the shortest distance, thus showed the highest TOC concentration of the renovated water samples. The additional movement in the aquifer (mostly lateral to the North Well and vertical to the perforated section of the Center Well) thus produced more removal of organic carbon.

Previous work at the Flushing Meadows project showed that the BOD of the renovated water was essentially zero, indicating that most of the organic carbon in the renovated water must be associated with organic compounds that are not readily degraded in the soil and aquifer. Some of the organic carbon undoubtedly is in the form of humic and fulvic acids. However, trihalomethanes and other organohalides, plus plasticizers, pesticides, and other compounds entering the sewage effluent via industrial wastes or from chemical products used in the household could be present. Chlorinated organics may also be formed by reactions between chlorine and organic compounds when raw water is treated for municipal water supply, and again when sewage effluent is chlorinated in the sewage treatment plant. The presence and identity of trace organics in renovated water is a major factor of concern in the potable reuse of such water, because the organics can include known or suspected carcinogens for man or animals.

The identity of the trace organics in the secondary effluent and in the renovated water from various wells was studied in the first part of 1980 by staff members of the Department of Environmental Science and Engineering of Rice University, Houston, TX (M. B. Tomson, J. Dauchy, S. Hutchins, C. Curran, C. J. Cook, and C. H. Ward) and by staff members of the Environmental Engineering and Science Program, Department of Civil Engineering of Stanford University, Stanford, CA (E. J. Bouwer, J. Graydon, and M. Reinhard).

Rice University Studies

On 24-27 January 1980, preliminary samples for trace organic analysis were obtained from the 23rd Avenue project. The existing pump in the 18-m Well used for sampling was a 0.9 m long, 10 cm diameter Berkeley Model #4AM8 all stainless steel (except for the hard-plastic impeller and the insulation-coated power cord) completely sealed submersible pump, rated at 38 ℓ/min. It has been suggested that most commercial electric pumps cannot be used to obtain groundwater samples for trace level organics analysis because trace level organics from the bearings, plastic components, etc. are continuously being released to the water. To test the effects of such a pump on the sampling procedure, 2 samples were taken at the same time, one using the installed submersible pump and one using an all glass and Teflon nitrogen-powered pump developed at Rice University.[1/] The glass and Teflon pump was lowered down the 18-m Well casing to about 1 m below the submersible pump. During the 12 hours required for sampling, the submersible pump discharged about 27 m^3 water through a hose to basin 3. The 60-cm^3/min flow required for the XAD-2 adsorption column was obtained via a 0.64-cm steel tee screwed into the submersible pump riser pipe a few inches above the casing top. Sampling consisted of passing 10 to 50 ℓ of groundwater or sewage through a 15-cm by 0.9-cm i.d. Teflon column filled with purified XAD-2 resin. A variable speed peristaltic pump (Masterflex) located after each XAD-2 resin column was used to control the water flow rate through the columns at about 60 cm^3/min. Organic compounds were adsorbed and concentrated on Amerlite XAD-2 macroreticular resin (Rohm and Haas, Philadelphia, PA). This resin is a low-polarity, styrene-divinylbenzene copolymer with excellent surface characteristics for the adsorption of lipophilic contaminants.

A gas chromatogram of each of the extract concentrates from the columns was obtained from a Tracor 560 GC with FIDs using a 50-m fused silica Hewlett-Packard SP 2100 WCOT capillary column. The chromatograms were recorded on a Spectra-Physics 4100 integrating computer. A portion of each sample was then spiked with D_8Napththalene and mass

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1/ Tomson, M. B., S. Hutchins, J. M. King, and C. H. Ward. 1980. A nitrogen powered continuous delivery, all-glass teflon pumping system for ground-water sampling from below 10 meters. Ground Water 18, 444-446.

spectral analyses were performed on a Finnigan 4000 MS using a matched GC capillary column. GC confirmation was performed by known addition or by retention time matching on as many compounds as could be obtained. In most cases quantitation was based upon internal standards using the SP 4100 integrated peak areas. Since the results from the two pumps were quite similar, a more extensive sampling of the effluent and renovated water at the 23rd Avenue project was made February 26 to March 1, 1980, using the commercial pumps only.

A summary of the refractory volatile organic (RVO) compounds found in the February 26-March 1 samples is presented in Table 2. The "purity" index in Column 2 is a measure of how well a library mass spectrum matches the corresponding sample spectrum. From experience with other but similar groundwater and sewage samples, it was found that the average purity index and standard deviation of compounds subsequently confirmed by GC retention time matching was about 830 ± 150. Therefore, only compounds which have been either confirmed by GC retention time matching ("x" in Column 3) or have a "purity" ⩾ 680, are reported. The compounds reported in Table 2 constitute 54%, by number, of compounds identified, but from 75 to 85% of the RVO mass (estimated by area under the GC trace). In addition to the RVO's listed, 3-methylpentane, 2-isopropoxy-1-propanol, ethyl acetate, chloroform, 2,4,6-trimethyl-1,3,5-trioxane, and 1,1,1-trichloroethane with purity indexes 929, 793, 916, 993, 861, and 959, respectively, were identified by mass spectral analysis to be under the solvent peak, prior to trichloroethylene.

The compounds in Table 2 are listed in the approximate order that they elute from the capillary GC column with a few exceptions of isomers which have been grouped together for illustration. The Mass Spectral Search System (MSSS) used in this study to assist in compound identification often fails to correctly differentiate between closely related isomers such as the various trialkyl-benzenes, tetralkyl-benzenes, dichloro-benzenes, methyl-napthalenes, and different high molecular weight alkanes, but for "purity" ⩾ 680 rarely is the compound class or overall carbon number in error. If the compound was also confirmed by GC retention time matching, there is little uncertainty in its specific identity. An overall estimate of the uncertainty in the concentrations was made by various repetitive injections, extractions, etc. and probably is within a factor of ± 1.0 to 2.0 of the value for compounds at concentrations < 0.1 μg/ℓ to about ± 0.2 to 0.5 of the value reported for concentrations > 0.1 μg/ℓ.

For the analytical reasons discussed above and because compounds of one chemical class often have similar biological, physical, and chemical properties, the sums of compound concentrations by chemical class are listed in Table 3. The overall weighted average RVO removal was 92%. When all compounds were considered, regardless of "purity" index, the removal was from 16.578 $\mu g\text{-}l^{-1}$ to 2.245 $\mu g\text{-}l^{-1}$, or 86.4%. The difference was not clearly attributable to any given class. From Table 3 it can be seen that most classes of compounds were removed from 90 to 100%. Noted exceptions were chloroalkanes, alkylphenols, alkanes, phthalates, and amides.

The phthalate data may be in error because previous analyses of other sites and other data showed phthalate removals ranging from 70 to 80%. However, if the phthalate data is omitted, the Δ RVO% only increases from 92 to 94%.

Stanford University Studies

On 27-28 February 1980, samples of secondary effluent entering and leaving the infiltration basins, and of renovated water from various wells were taken and shipped to Stanford University for volatile organic analysis (VOA) [2/], closed-loop stripping analysis (CLSA) [3/], and hexane solvent extraction analysis (SEA) [4/]. Results of the low molecular weight halogenated organic analyses (volatile organic analysis or VOA) are shown in Table 4. Compounds at or below the detection limit of 0.1 μg/ℓ were:

Carbon tetrachloride	CCl_4
Bromodichloromethane	$CHBrCl_2$
Dibromochloromethane	$CHBr_2Cl$
Bromoform	$CHBr_3$

Traces of these compounds were detected, but they were insignificant and/or due to possible solvent contamination.

The VOA results (Table 4) indicate that volatilization losses are probably the major removal mechanism for these compounds. Removals of at least 60% were observed between infiltration basin inflow (secondary effluent) and basin outflow. The infiltration basin outflows had lower concentration fluctuations than the inflows. Thus, the basins appeared to damp out some of the influent concentration variations. The halogenated organic concentrations in the 18-m Well and 30-m Well were similar to the basin inflow concentrations. Thus, there was little or no reduction in concentration of these halogenated organics during soil passage. Concentrations in the water from the North Well, however, were considerably lower than in that from the 18-m and 30-m Wells, either as

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2/ Henderson, J. E., G. K. Peyton and W. H. Glaze, 1976. A convenient liquid-liquid extraction method for the determination of halomethanes in water at the parts-per-billion level. In Identification and analysis of organic pollutants in water. L. H. Keith (ed.), Ann Arbor Science Publishers, Inc., Ann Arbor, MI, 105-112.

3/ Grob, K. and F. Zurcher, 1975. Stripping of trace organic substances from water--Equipment and procedures. Jour. Chromatogr. 117, 285-299.

4/ Reinhard, M., J. E. Schreiner, T. Everhart and J. Graydon, 1979. Specific compound analysis by gas chromatography and mass spectrometry in advanced treated waters. Presented at the NATO/CCMS Conference of practical application techniques, Reston, VA, May 1, 1979.

a result of sorption, degradation, or dilution by Salt River water (flooding period).

Chloroform showed the greatest reduction among the 4 compounds. For example, chloroform in North Well water was lower than in basins 1 or 4 outflows, whereas, the other 3 compounds were higher in North Well water. Variations in basins 1 and 4 inflow concentrations probably account for the high values of 1,1,1-trichloroethane and tetrachloroethylene found in the 18-m Well and the 30-m well.

The compounds identified by CLSA were primarily hydrocarbons, alkylated benzenes, and a few chlorinated benzenes (Table 5). Concentrations in the water leaving the basins were significantly lower than in water entering the basins. This was probably due to volatilization losses from the infiltration basins, as for the VOA compounds. Most of the CLSA compounds identified in basin influents also appeared in the observation wells, but at lower concentrations. The longer underground travel to the North Well did not significantly alter the concentrations compared to those for the 18- and 30-m Wells in the center. Many of the alkylated aromatics are biodegradable, and are suspected to be removed in the system by biological action as evidenced by the low concentrations in the water from the 18-m and 30-m Wells. The mass spectra of several C_3-substituted benzenes (C_9H_{12}) were not differentiated, so no further identification could be achieved.

The chlorinated benzenes and naphthalene showed little reduction during soil percolation. Although these compounds have been found biodegraded in aerobic column studies at Stanford University, no anaerobic conditions were found under which these compounds were degraded (unpublished results). With the high organic loading during infiltration, it is likely that most of the soil profile was anaerobic except for a small aerobic zone at the soil surface. Therefore, significant biological removal of the chlorinated benzenes and naphthalene in the anaerobic aquifer would not be expected. This also accounts for no further removals with longer underground travel to the North Well.

Compounds identified by solvent extraction analysis (SEA) included (Table 6):

phthalates	- plasticizers
chlorinated anisoles	- possible methylation products of chlorophenols
DDT, lindane	- pesticides

These compounds are not as volatile or biodegradable as the compounds measured by VOA and CSLA, and many of them appeared in the renovated water. Significant reduction in concentration between basin inflows and outflows occurred for some of the compounds identified by SEA. Some were also reduced during passage through the soil. This was most likely due to sorptive processes. However, the compounds generally were present at concentrations near the detection limit, except for the phthalates, making it difficult to make positive conclusions about observed removals.

A more systematic study of the trace organics in the sewage effluent and renovated water was begun in September 1980, sampling on two days each week. For the effluent, samples were obtained at different times of the day and at different points in the infiltration basins. The trace organics identification again was done by Stanford University, in cooperation with the Western Regional Research Center laboratory of the U. S. Department of Agriculture (SEA-AR) in Albany, California. The first series of samples and analysis were done to characterize the trace organics before chlorination of the effluent, which started routinely at the treatment plant in the middle of November. Starting in April 1981, a second series of 2-month sampling will be done to see if there is any effect of the chlorination on the trace organics in the plant effluent and in the renovated water from below the infiltration basins. The results of these studies will be presented in one report next year.

II. ANALYSIS OF VADOSE ZONE SAMPLES

More information on the quality of deep percolation water from irrigated fields is needed to accurately assess the effect of irrigation on groundwater quality. In many areas the water table is presently decreasing faster than the downward movement of the deep percolation water. Some idea of the quality of the deep percolation water can be obtained by looking at the water in the vadose zone. A number of dry wells are presently being installed in the Phoenix area to rapidly dispose of surface runoff. The chemical compositions of the water in the vadose zone was determined from soil samples taken during the construction of two dry wells. The wells were dug with a bucket type drill rig. The rig drilled a 4-foot diameter hole with each bucket removing about 1-foot depth of soil.

The first well was located southeast of Alma School and Warner in Chandler, and was in a area that had been under irrigation for a number of years. Soil samples were taken at various depths as the hole was dug. The depth of the hole was 52 feet. Sand was hit at 39 feet. Gravimetric water content and particle size were determined for each sample (Table 7). The top 7 feet consisted of a loam soil. At 10 to 14 feet, the texture changed to sandy loam and silt loam. From 15 to 38 feet, the silt and clay content was higher and the texture ranged from silty clay to loam. Below 39 feet was medium sand.

The water content increased from 10-14% in the top 10 feet to 20-26% from 12 to 38 feet. The water content of 48% at 25 feet appears to be unreasonably high. The water content in the sand was 4 to 5%. The water contents below 12 feet are essentially at field capacity, which ranges from 22 to 30% for loam and clay loam soils. The 4 to 5% in the medium sand is also close to field capacity. The last irrigation on the field probably was within 6 to 12 months. The sand-loam interface did not result in a restriction of flow as the water content above the interface was about at field capacity.

The concentration of total dissolved salts (TDS), Na^+, Mg^{++}, Ca^{++}, Cl^-, $NO3^-$, and $NH4^+$ were determined from soil saturation extracts and are shown in Table 7. The salt content is expressed as mg/ℓ of original soil water. Above the sand, the TDS content ranged between 1500 and 2900 mg/ℓ except for the 19-foot sample, where it was 4925 mg/ℓ. The TDS content in the sand was about 5000 mg/ℓ. The average TDS content of the 12 to 38-foot zone was 2570 mg/ℓ. The average TDS content of the irrigation water for the 1971-80 period was 627 mg/ℓ. Thus, the irrigation efficiency would be 76% assuming there was a salt balance in the root zone. The average NO_3 concentration was 204 mg/ℓ, which is about 4.5 times higher than the 45 mg/ℓ standard for drinking water. The NO_3 concentration was greatest at 16 feet.

The second well, located at 18th Street and Missouri, Phoenix, was at the lower end of a church parking lot. The church has been at that location for 4 years. Previous to the church construction the lot had been vacant for several years. Rain water draining from the parking lot was the only source of deep-percolation water in the past 4 years.

The soil is a fairly uniform fine sandy loam to a depth of 66 ft. A rock formation was hit at 66 feet. The average composition of the soil was 54% sand, 37% silt, and 9% clay. The gravimetric water content was also fairly uniform ranging from 11 to 21% and averaging 14.4%. Field capacity of fine sandy loam would be around 14%. The rock formation did not act as a restricting layer.

The composition of the soil water is shown in table 8. The average TDS concentration was 756 mg/ℓ which is about 3.5 times less than that from the irrigated field. The lower TDS content is reasonable since rain water has been the only source of water. The nitrate concentration was about half of that in the irrigated field and the calcium and magnesium concentrations were about the same. The largest difference was in the sodium and cloride concentrations. The average nitrate concentration was 103 mg/ℓ. There are two areas of higher nitrate concentrations, one at 10-16 feet and the other at 36-47 feet. The higher concentrations are probably due to nitrate applications to the trees and shrubs in the area. The two distinct "peaks" are probably the result of applications at different times with excess rain leaching the nitrate below the root zone.

SUMMARY AND CONCLUSIONS:

The work at the 23rd Avenue rapid infiltration project in 1980 consisted of studying the effect of the lower algae content in the secondary effluent (due to construction of a bypass canal around the 80-acre pond in 1979) on infiltration rates, the effect of breaking up the surface soil in the basins on infiltration rate, the response of the groundwater table to recharge, and the quality of the renovated water in relation to that of the secondary effluent (including viruses and trace organics). The wastewater renovation work is nearing completion and its scope will be significantly reduced after the summer of 1981. Most of the effort of the Subsurface Water Management Group will then be directed toward the effect of irrigated agriculture on recharge and quality of underlying groundwater (including transport of water and chemicals in the vadose zone). To get some insight into vadose zone conditions in irrigated desert valleys, soil samples were obtained during drilling of storm-runoff injection wells in the Salt River Valley. The soil samples were analyzed for particle size distribution, water content, and chemical composition of the water.

Flooding schedules of the infiltration basins ranged from one week flooding and three weeks drying in winter to two weeks flooding and two weeks drying in summer. The average hydraulic loading of the four 10-acre basins was 82 m per year. Of this amount, 21 m or 26% infiltrated in the first half of the year. In June and July, the surface soil of the basins was ripped with a grader, which more than doubled the infiltration rates. Based on these results, it is projected that hydraulic loading rates of 90 m/year can be maintained, even if ripping the surface soil must be repeated each year. The cost of ripping in 1980 was about $22/ acre or only $0.18 per acrefoot of increased hydraulic loading obtained. This is an inexpensive way of increasing the hydraulic capacity of the system. The suspended solids content of the effluent entering the infiltration basins ranged between 5 and 25 mg/ℓ and averaged 13.4 mg/ℓ. Thus, the bypass channel in the 80-acre pond prevented growth of algae in the sewage effluent and associated clogging of the soil in the infiltration basins.

Depth to groundwater below the basins ranged from 3 to 13 m. The rise of the groundwater mound due to flooding the center basins was used to calculate the transmissivity of the aquifer, yielding a value of 84,000 m^2/day. Based on this result and on data from previous well pumping tests, a design value of 50,000 m^2/day is suggested for the transmissivity of the local aquifer.

The renovated water pumped from various wells in the project showed an average suspended solids content of 1 to 2 mg/ℓ and an average salt content of 786 mg/ℓ. The latter was 44 mg/ℓ higher than that of the secondary sewage effluent. The total N concentration of the secondary effluent averaged 17 mg/ℓ (15.6 as ammonium) and that of the renovated water from the production well in the center of the project 5.3 mg/ℓ (5.2 as nitrate). Thus, 69% of the nitrogen in the sewage water was removed by the soil-aquifer system. Phosphate removal was 92% (from 5 to 0.42 mg/ℓ). Fecal coliform concentrations in the renovated water were higher than before, possibly as a result of breaking up the surface soil. The average fecal coliform concentration in the renovated water from the center well was 24/100 mℓ, but peaks of 140 and 160/100 mℓ were also observed. Chlorination of the sewage effluent, which was started by the treatment plant in November 1980, should reduce fecal coliform counts in the renovated water. Virus concentrations in the renovated water, using samples of 800 to 2000 liters, averaged 0.15 PFU/100 ℓ in January and 1 PFU/100 ℓ in June. Total organic carbon concentrations averaged 9.3 mg/ℓ for the secndary sewage effluent and 1.9 mg/ℓ for the renovated water from the center well. Since the BOD of renovated sewage water was essentially zero in previous studies, most of the residual organic carbon in the renovated water must be due to refractory or trace organics, which could include carcinogens or other toxic compounds.

Identification of the trace organics in renovated water and sewage effluent by Rice University and Stanford University showed a wide spectrum of organic compounds, ranging from the volatile trihalomethanes to the heavier compounds like chlorobenzenes and other aromatics, plasticizers (phtalates), and insecticides (DDT, lindane). Renovated water obtained with a special glass-teflon sampling pump to minimize contamination of the water with extraneous organic carbon yielded essentially the same spectrum of organics as that sampled from the commercial pumps in the wells. Thus, the pumping rates from the wells were sufficiently large for the introduction of other organics from oil, grease, plastic components in the pump, insulation of electrical wire, etc., to be insignificant.

Concentrations of trihalomethanes were below the maximum interim limit of 0.1 mg/ℓ for drinking water. Concentrations of other compounds were on the order of nanograms to micrograms per liter. Removal processes of trace organics in the soil-aquifer system include volatilization (mostly in the infiltration basins and for the lighter compounds like chloroform and tetrachloroethylene), biological decay (some degrade under aerobic conditions, others under anaerobic conditions, and some not at all), and adsorption to the soil and aquifer materials. Because of these, TOC-concentrations in renovated water tend to decrease with increasing time and distance of travel in the soil-aquifer system.

Trace organics are the main concern in the potable reuse of renovated sewage effluent. Thus, while the renovated water from the 23rd Avenue rapid-infiltration project would be suitable for unrestricted irrigation and recreational lakes, potable use of the water would require additional treatment. This treatment, however, would be much more effective and economical when applied to the renovated water from the soil-aquifer treatment system than to the sewage effluent directly from the treatment plant.

The studies on the quality of water in the vadose zone using soil samples from dry-well drilling in the Salt River Valley indicated that below an area with a long history of irrigation, the salt content of the water was 2570 mg/ℓ (average for the top 52 ft of the vadose zone). Since the salt content of the irrigation water had averaged 627 mg/ℓ, the irrigation efficiency was around 76% (assuming no precipitation or dissolution of salt in the vadose zone). The nitrate content of the water in the vadose zone at the same site was 204 mg/ℓ (45 mg/ℓ as

NO_3-N), which is almost 5 times as high as the maximum limit for drinking water. Samples from another dry well that was installed at the edge of a church parking lot showed that the water in the top 66 ft of the vadose zone contained 765 mg/ℓ salt and 103 mg/ℓ nitrate. Thus, the salt content was lower (probably because of infiltration of rainfall runoff from the parking lot), but the nitrogen content was still relatively high (possibly due to fertilization of the landscaped area around the parking lot). Additional studies are planned to obtain a better idea of water quality in the vadose zone and its potential effect on the quality of underlying groundwater.

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TABLE 1. VIRUS CONCENTRATIONS AND ISOLATES FROM CONCENTRATED RENOVATED WATER SAMPLES OF THE 23rd AVENUE PROJECT

Sampling date	Well	Sample size ℓ	Virus Count (PFU/100 ℓ)	Viruses isolated
2 Jan. 1980	North	800, 2000	0.1	Coxsackie-B3
	18-m	1800, 400	0.2	Coxsackie-B3
10 Jun. 1980	North	1200, 1200	1.5	Coxsackie-B4
	18-m	1200, 1200	2.0	Polio-1, Coxsackie-B3
	Center	1200, 1200	1.3	Polio-1

TABLE 2 (continued)

29.	1,6-Dichloro-1,5-cyclooctadiene	791				.011				
30.	2,3-Dihydro-1H-inden-1-one	866		.087	.099					
31.	1-(4-Ethylphenyl)ethanone	716		.006	.026					
32.	p-Isopropylphenol	491	x	.061	.028					
33.	α-Terpineol	581	?	.045	<.008					
34.	2-Methylnaphthalene	581	x	.226	.396					
35.	1-Methylnaphthalene	811	x	.050	.059					
36.	3,3-Dimethylhexane	850		IP**	IP	.012	.004	.009	.011	.009
37.	p-t-Butylphenol	748		.125	IP					
38.	p-t-Butylphenol	722		.150		.118	.040	.048	.069	.046
39.	m-t-Butylphenol	849	x	.189	.116	P				
40.	p-t-Butylphenol	738		.819	.907	.069	.035	.090	.097	.074
41.	1H-Indole	662	x	.009	.086					
42.	Skatole	901		.030	.031					
43.	Undecane	773					.004			
44.	3,5,24-Trimethyltetracontane	742		.095	.110					
45.	Dimethylphthalate	585	x	.023	.015					
46.	1,2-Dihydro-2,2,4-tri-methylquinoline	720				.093	P	.019	.021	.056
47.	2,6-Di-t-butyl-p-benzoquinone	760		.022	.037	.005	P	P	P	P
48.	O-Decylhydroxxylamine	687		.005	<.008					
49.	2,6-Di-t-butyl-p-cresol	887		.267	.250	.056	.200	.071	.096	.079
50.	t-Butyl-4-methoxyphenol	687		.008	.131					
51.	α-Hydroxybenzeneacetic acid	779		.008	.082					
52.	1,6-Dioxacyclododecane-7,12-dione	735				.021		P	P	P
53.	o-Phenylphenol	751		.008	<.008					
54.	Butoxymethylbenzene	760				P	.005	.007	.008	.005
55.	Nonylbenzene	808		.008	.680?					
56.	Diethylphthalate	905	x	.231	<.008	.017	P	P	P	P
57.	2-Methylthiobenzothiazole	711	x	.193	.202	.028	.004	.023	.016	.011
58.	Benzophenone	894	x	.233	.285	.045	.016	.014	.014	.009
59.	2-Propyl-1-heptanol	803				.005	.003	.012	.008	.006
60.	p-(1,1,3,3-Tetramethylbutyl)phenol	923	x	.757	.809	.017	.010	.014	.013	.012

(continued)

TABLE 2 (continued)

61.	p-(2,2,3,3-Tetramethylbutyl)phenol	896	.156		.103	.107	.053	.072	.042
62.	N-(3-Methylphenyl)acetamide	773	IP	IP	.110	.114	.030	.041	.025
63.	Hexadecane	703	.052	.057					
64.	Hexatriacontane	852	.035	.036	.130	.271	.095	.028	.090
65.	Hexatriacontane	850	.120	.022	P	P	P	P	P
66.	4,6,8-Trimethyl-1-nonene	849				.013			
67.	Dibutylphthalate	957	.248	.260	.316	.729	.274	.314	.239

* P - indicates compound was present, but at too low concentration to estimate.

** IP - indicates that the corresponding GC and GC/MS peak could not be reliably separated from background peaks.

TABLE 3. REFRACTORY VOLATILE ORGANICS ($\mu g\text{-}l^{-1}$) BY CLASS, 23RD AVE. PROJECT, PHOENIX, ARIZONA

	Class (Typical Example)	Purity ≥ 680 Average sewage	Average 18-m W	ΔRVO%
1.	Chloroalkanes (tetrachloroethylene)	0.136	0.056	70
2.	Chloroaromatics (p-dichlorobenzene)	0.922	0.055	94
3a.	Alkylbenzenes (o-xylene)	5.943	0.123	98
3b.	Alkylphenols (p-isopropylphenol)	1.624	0.241	85
4.	Alkylnaphthalenes (2-methylnapthalene)	2.101	0.000	100
5a.	Alkanes (hexatriacontane)	0.671	0.193	71
5b.	Alcohols (2,4-dimethyl-3-hexanol)	0.132	0.006	95
5c.	Ketones (2,6-d-t-butyl-p-benzoquinone)	0.197	0.004	98
6.	Phthalates (dibutylphthalate)	0.385	0.379	2
7.	Indoles, Indenes (IH-indole)	1.736	0.071	96
8.	Amides (N-[3-methylphenyl]acetamide)	0.212	0.055	74
9.	Alkoxyaromatics (butoxymethylbenzene)	0.107	0.010	91
TOTAL		14.216	1.193	

$$\Delta RVO\% \quad \frac{\sum Sew - \sum 18\text{-}m\ W}{\sum Sew} \times 100\%$$

TABLE 4. RESULTS OF VOLATILE ORGANIC ANALYSIS (VOA). μg/ℓ

Sample	Chloroform $CHCl_3$ Samples	Ave.	1,1,1 Trichloroethane Cl_3CCH_3 Samples	Ave.	Trichloroethylene $Cl_2C{=}CClH$ Samples	Ave.	Tetrachloroethylene $Cl_2C{=}CCl_2$ Samples	Ave.
Basin 1 inflow 2/28/80	4.92 5.19	5.06	4.08 4.48	4.28	1.54 1.73	1.64	6.44 7.40	6.92
Basin 1 outflow 2/28/80	1.28 1.30	1.29	1.98 1.81	1.90	0.23 0.36	0.30	2.09 1.78	1.94
Basin 4 inflow 2/29/80	4.47 5.33	4.90	7.50 10.1	8.80	1.33 1.76	1.55	7.27 11.3	9.29
Basin 4 outflow 2/29/80	1.60 1.69	1.65	1.78 1.76	1.77	0.33 0.34	0.34	1.31 1.15	1.23
North Well 2/28/80	0.32 0.32	0.32	1.92 2.22	2.07	0.89 1.05	0.97	3.20 3.46	3.33
North Well 2/29/80	0.25 0.27	0.26	3.16 3.06	3.11	0.87 0.88	0.88	2.98 2.65	2.82
18-m Well 2/28/80	1.85 1.86	1.86	8.55 8.30	8.43	1.73 1.71	1.72	10.8 10.6	10.7
18-m Well 2/29/80	1.73 1.74	1.74	10.1 8.24	9.17	1.96 1.64	1.80	13.7 10.3	12.0
30-m Well 2/28/80	2.13 1.99	2.06	6.29 5.98	6.14	2.16 2.52	2.34	10.8 11.7	11.3

Table 5. Results of closed-loop stripping analysis (CLSA). ng/ℓ

Compound	Basin 1 Inflow	2/28/80 Outflow	Basin 4 Inflow	2/29/80 Outflow	18-m Well 2/28/80	18-m Well 2/29/80	30-m Well 2/28/80	North Well 2/28/80	North Well 2/29/80
+Ethylbenzene C_8H_{10}	1890	165	2285	355	20	60	85	35	205
meta and para xylene C_8H_{10}	13,700	385	3610	440	45	140	245	110	995
Unknown	500	70	1535	250	—	—	—	—	—
ortho xylene C_8H_{10}	5400	185	2685	—	80	120	215	120	515
normal dodecane $C_{12}H_{26}$	1580	140	1970	400	—	—	—	—	—
Unknown (Iso-butylmethyl acetal $C_7H_{16}O_2$?) *	—	—	—	—	115	215	190	15	60
2,2,4-trimethyl heptane $C_{10}H_{22}$	1330	335	2685	555	—	—	15	—	—
C_3-benzene C_9H_{12}	2890	155	2565	—	20	100	155	125	545
C_3-benzene C_9H_{12}	1985	95	2375	90	30	40	70	25	130
Unknown	1305	65	1500	—	30	50	55	20	100
C_3-benzene C_9H_{12}	4260	145	2380	—	25	85	100	40	455
ClC_8H_{17} (internal std.)	880	480	1060	555	240	235	175	190	175
C_3-benzene C_9H_{12}	1810	90	1400	—	35	45	60	20	155
+1,3-dichlorobenzene $C_6H_4Cl_2$	2020	340	1410	285	290	305	430	210	310
+1,4-dichlorobenzene $C_6H_4Cl_2$	3170	635	3255	945	890	980	1265	650	795
+1,2-dichlorobenzene $C_6H_4Cl_2$	4480	685	3415	710	1300	1440	1810	1015	1195
Unknown	155	—	505	40	20	40	45	30	85
+1,2,4-trichlorobenzene $C_6H_3Cl_3$	1150	—	1100	300	315	225	270	180	215
+naphthalene $C_{10}H_8$	940	150	785	260	395	210	590	170	410
$ClC_{12}H_{25}$ (internal std.)	500	500	500	500	300	300	200	200	200
2,2,4-trimethyl-penta-1,3-diol-isobutyrate $C_{10}H_{30}O_4$ *	645	120	570	270	165	480	160	75	70
Unknown	—	—	—	—	105	130	105	—	—
Unknown	835	105	285	250	160	360	330	100	145
Unknown	—	—	—	—	635	610	115	—	—
$ClC_{16}H_{33}$ (internal std.)	220	375	115	225	200	810	140	105	120

\+ Quantified using response factors determined with standards.
All other concentrations are relative to the internal standard $ClC_{12}H_{25}$ (response factor = 1.0).

— Below detection limit of 10 ng/ℓ.

* Evidence: MS comparison. E. Stenhagen, S. Abrahamson, F. W. McLafferty (eds), Registry of Mass Spectral Data, John Wiley & Sons, New York, NY. 1974.

Table 6. Results of solvent extract analysis (SEA).* ng/ℓ

Compound	Basin 1 Inflow	2/28/80 Outflow	Basin 4 Inflow	2/29/80 Outflow	18-m Well 2/28/80	18-m Well 2/29/80	30-m Well 2/28/80	North Well 2/28/80	North Well 2/29/80
Unknown	1420	65	2170	330	25	50	25	—	—
Unknown	120	170	490	160	20	10	10	—	—
+2,3,5,6-tetrachloroanisole $C_7H_4OCl_4$	—	—	—	—	35	—	—	—	—
+diethyl phthalate $C_{12}H_{14}O_4$	8830	12,700	35,300	8620	8610	4550	9500	1560	2100
+2,3,4,5-tetrachloroanisole $C_7H_4OCl_4$	—	—	—	—	20	—	20	—	10
+pentachloroanisole $C_7H_3OCl_5$	—	—	—	—	730	70	205	35	70
+lindane $C_6H_6Cl_6$	20	30	75	20	15	—	—	—	—
Unknown	1080	10	1850	55	—	—	—	—	—
diisobutyl phthalate $C_{16}H_{22}O_4$	45	20	80	—	30	—	—	—	—
Unknown	1880	135	3000	630	45	35	50	—	—
Unknown	85	15	115	50	130	55	100	35	40
Unknown	185	115	280	100	30	—	15	35	—
Unknown	25	—	—	20	35	35	35	50	30
+DDT $C_{14}H_9Cl_5$	10	10	20	—	10	—	10	—	—
hexabromobenzene (Internal Std) C_6Br_6	200	200	200	200	100	200	100	100	100
Unknown	—	185	150	45	35	80	80	—	—
+diethylhexyl phthalate $C_{24}H_{38}O_4$	1030	1140	5230	950	625	425	790	570	710

* Identification based on retention time.

\+ Quantified using response factors determined with standards.
All other concentrations are relative to the internal standard hexabromobenzene.

— Below detection limit of 10 ng/ℓ.

Table 7. Water content, salt concentration of soil water, and percent sand, silt, and clay at different depths for the Alma School and Warner dry well.

DEPTH	0	TDS	NA	MG	CA	NO3	NH4	CL	SAND	SILT	CLAY
FT	%			MG / LITRE		SOIL WATER				%	
0	14.2	2794	826	59	155	39	0	2218	36	30	34
3	10.0	1920	552	12	160	112	5	420	46	32	22
7	11.4	2639	767	105	246	294	30	706	36	44	20
10	10.4	2892	840	69	231	241	0	1144	63	30	7
12	22.2	2854	591	86	171	****	****	977	0	52	8
14	15.3	2635	812	110	118	328	0	1441	76	21	3
16	26.2	2125	799	82	137	373	0	1349	8	46	46
19	23.0	4925	1340	39	183	243	2	2648	20	49	31
25	48.6	2041	568	44	91	144	0	900	15	47	38
28	19.3	2354	667	25	73	101	0	907	33	44	23
33	21.1	2123	818	23	57	106	0	1393	26	55	19
38	20.8	1538	553	****	****	****	****	2019	45	36	19
43	5.1	5145	1804	141	78	274	0	1373	99	1	0
52	4.2	4724	1533	57	95	199	0	2833	99	1	0

Table 8. Water content, salt concentration of soil water, pH of soil water, and percent sand, silt, and clay at different depths for the 18th Street and Missouri dry well.

DEPTH	Θ	TDS	NA	MG	CA	NO3	NH4	CL	SAND	SILT	CLAY	PH
FT	%	MG / LITRE SOIL WATER							%			
0	14.4	484	46	28	121	40	0	72	47	46	7	6.2
4	14.5	625	67	36	144	39	5	71	**	**	**	6.6
7	16.6	574	56	46	144	121	6	45	**	**	**	7.0
10	17.9	539	36	42	131	99	0	58	54	37	9	6.8
13	12.7	874	66	51	202	261	0	65	**	**	**	6.7
16	10.7	974	67	67	213	391	2	88	**	**	**	6.9
19	12.7	533	47	24	107	49	1	63	47	46	7	7.0
22	14.3	477	39	41	95	85	1	27	**	**	**	7.0
25	14.6	539	57	55	106	72	0	24	**	**	**	6.8
28	21.2	367	39	35	63	13	0	17	42	50	8	7.1
36	14.4	806	75	58	136	144	0	46	**	**	**	7.0
39	14.2	742	69	11	113	144	0	51	**	**	**	7.0
41	16.6	642	60	54	102	117	0	25	54	35	11	7.0
44	7.8	1339	135	105	229	229	1	0	**	**	**	7.0
47	14.9	669	77	53	103	126	0	49	**	**	**	6.8
50	12.8	917	85	92	115	2	0	0	66	25	9	7.0
53	16.1	702	48	78	104	113	0	31	**	**	**	7.0
56	17.1	567	48	55	79	40	1	39	**	**	**	7.0
59	13.9	994	82	115	122	72	0	0	56	36	8	6.9
62	15.8	836	55	53	171	63	0	8	**	**	**	6.8
65	11.8	1358	111	138	170	45	1	43	**	**	**	7.1
66	11.8	1075	116	138	170	45	1	43	63	26	11	7.1

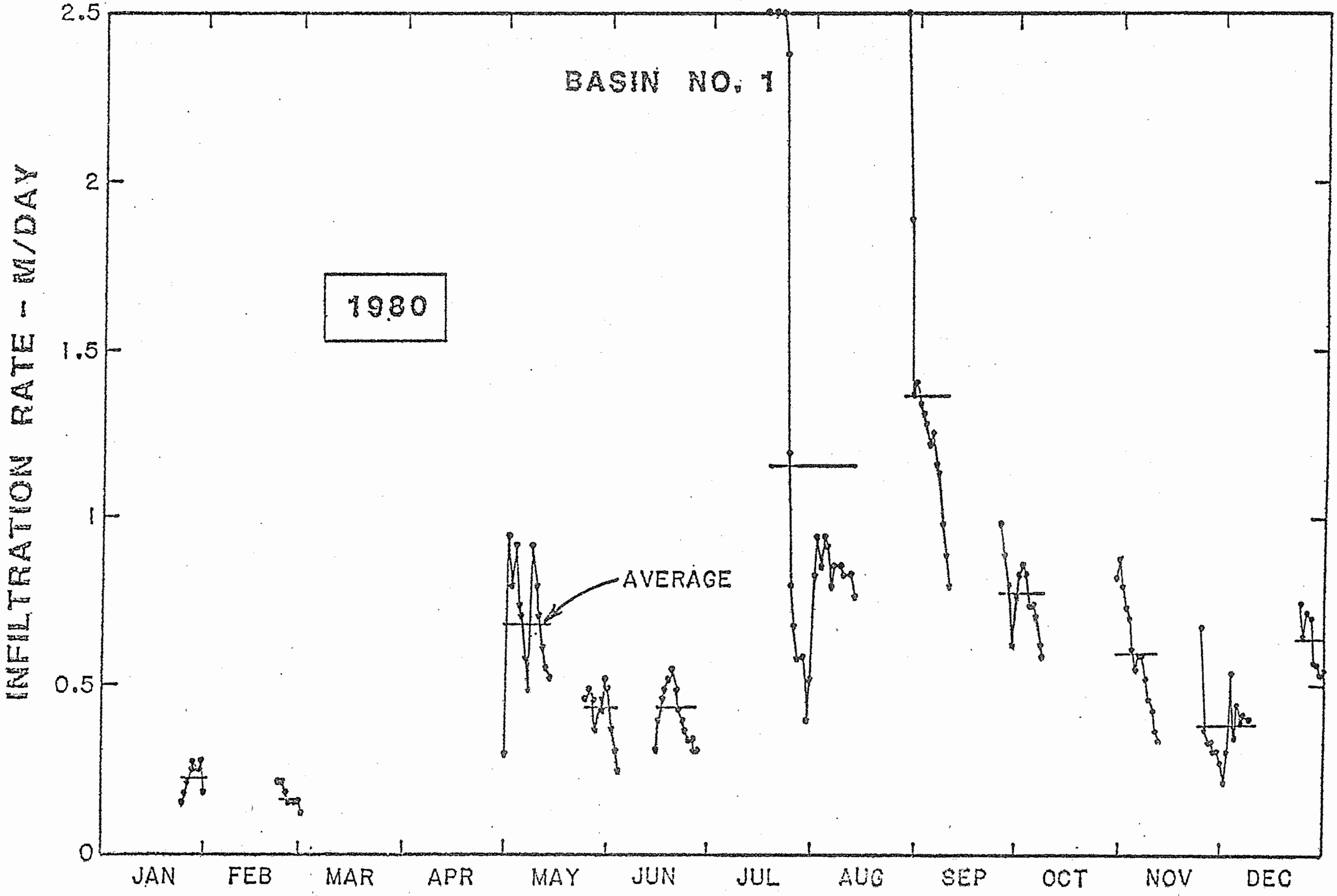

Figure 1. Infiltration rates for basin 1.

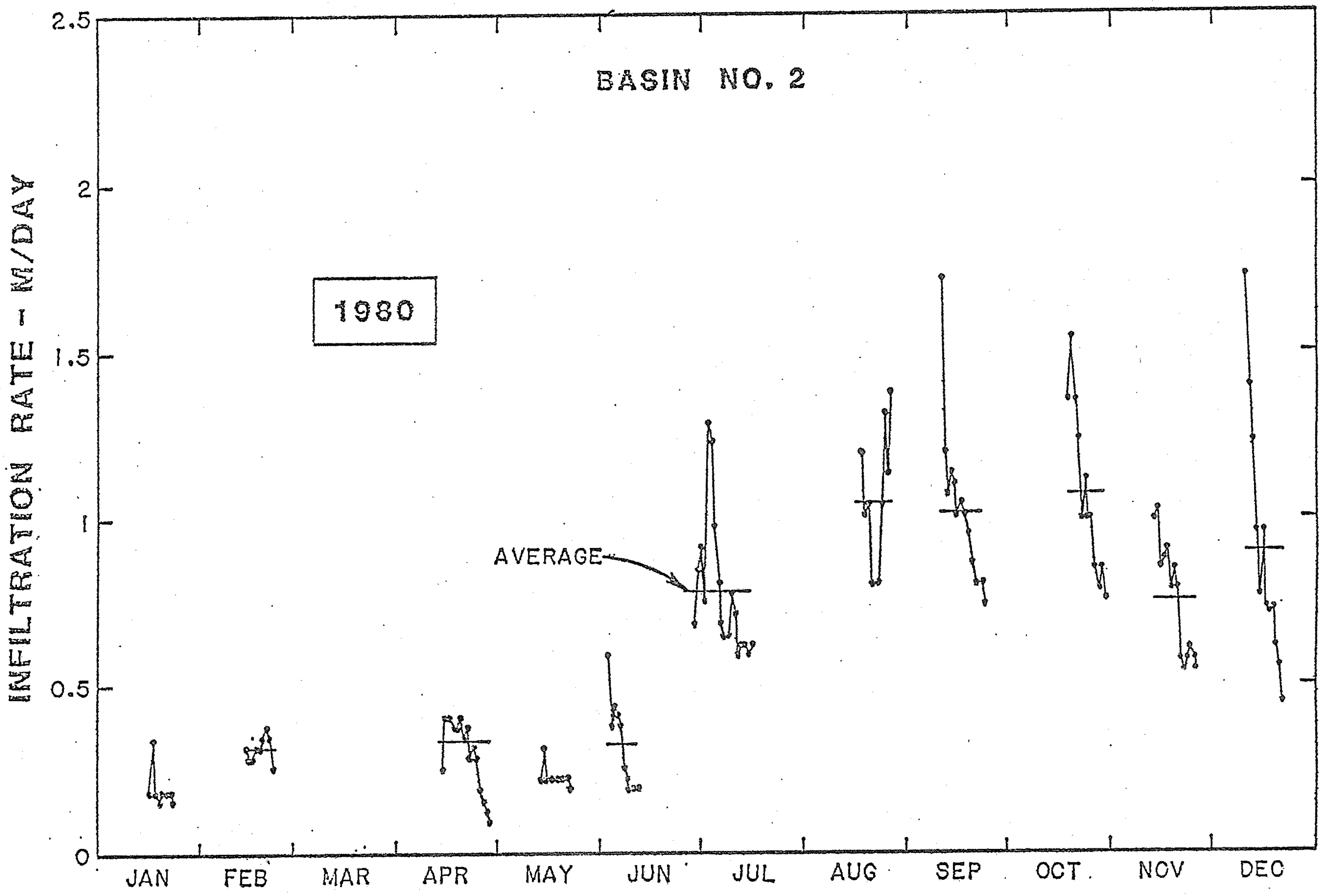

Figure 2. Infiltration rates for basin 2.

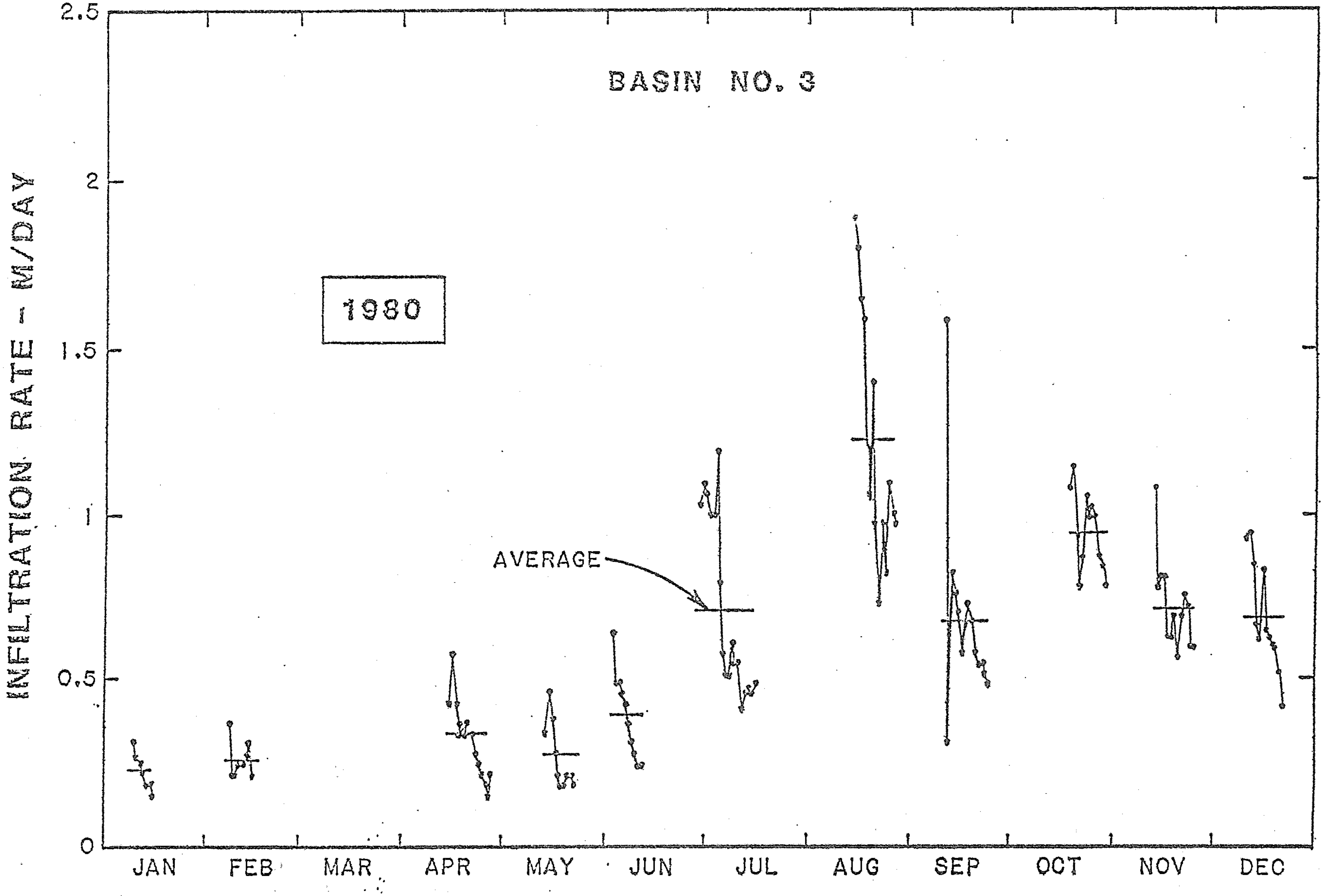

Figure 3. Infiltration rates for basin 3.

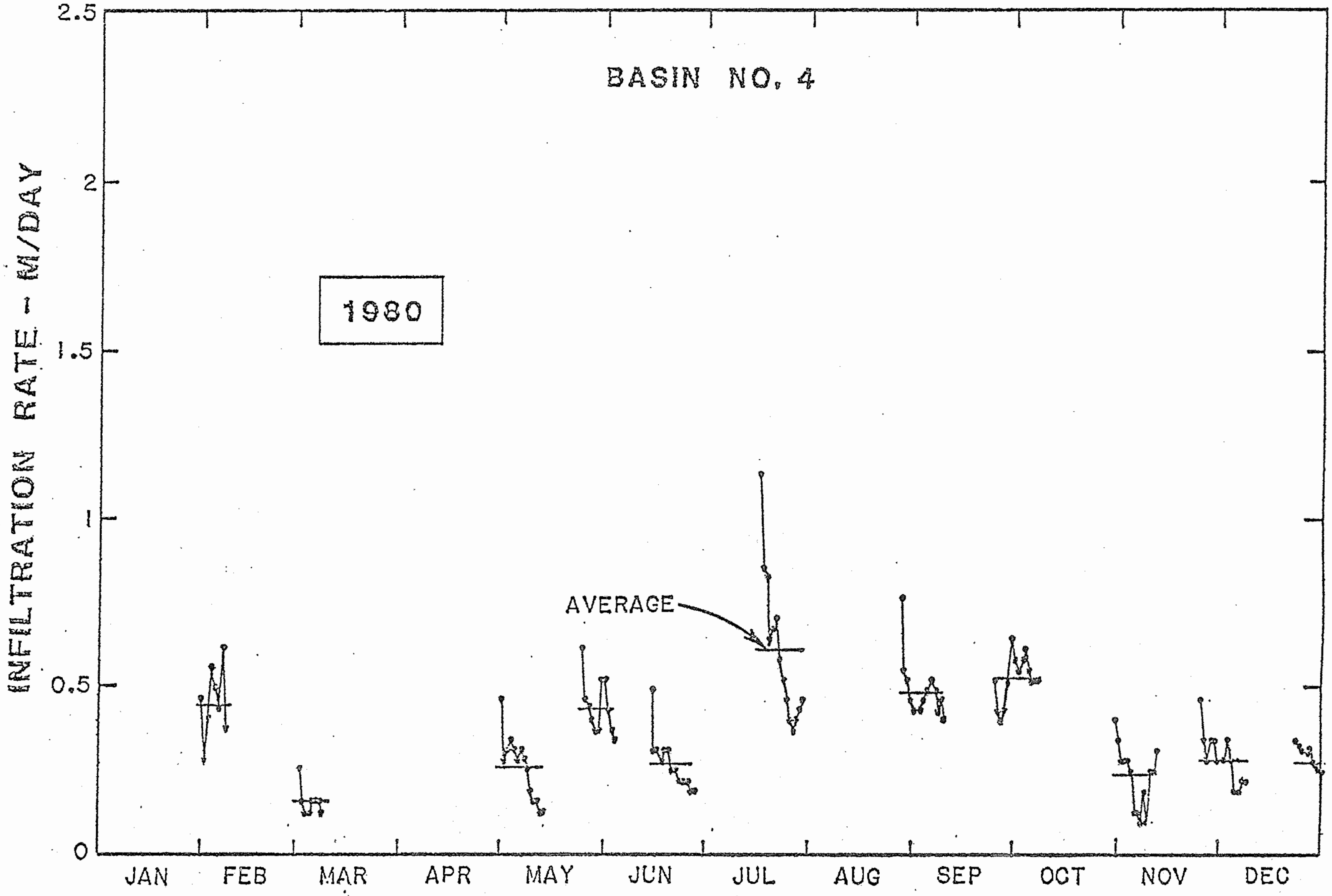

Figure 4. Infiltration rates for basin 4.

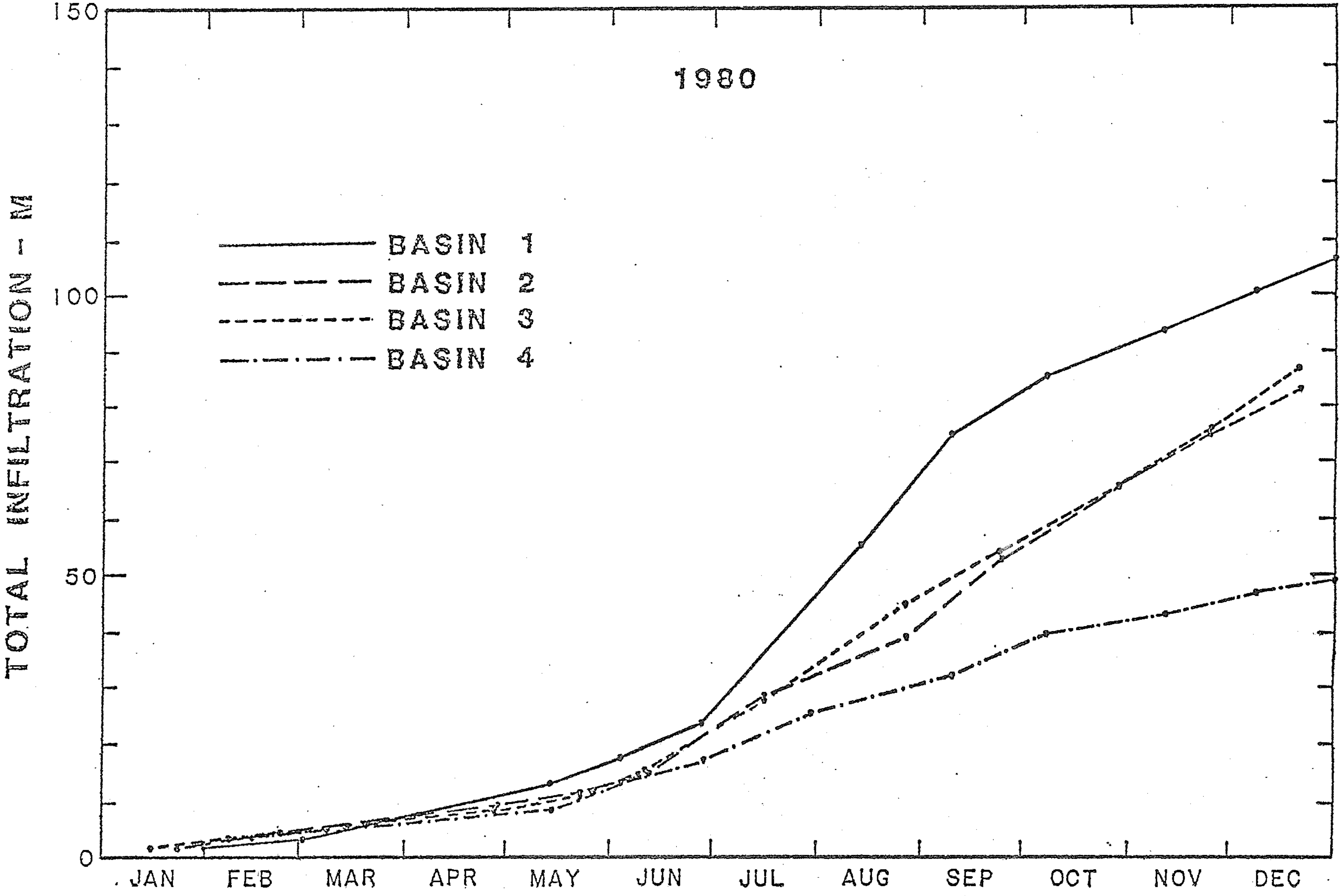

Figure 5. Accumulated infiltration for basins 1, 2, 3, and 4.

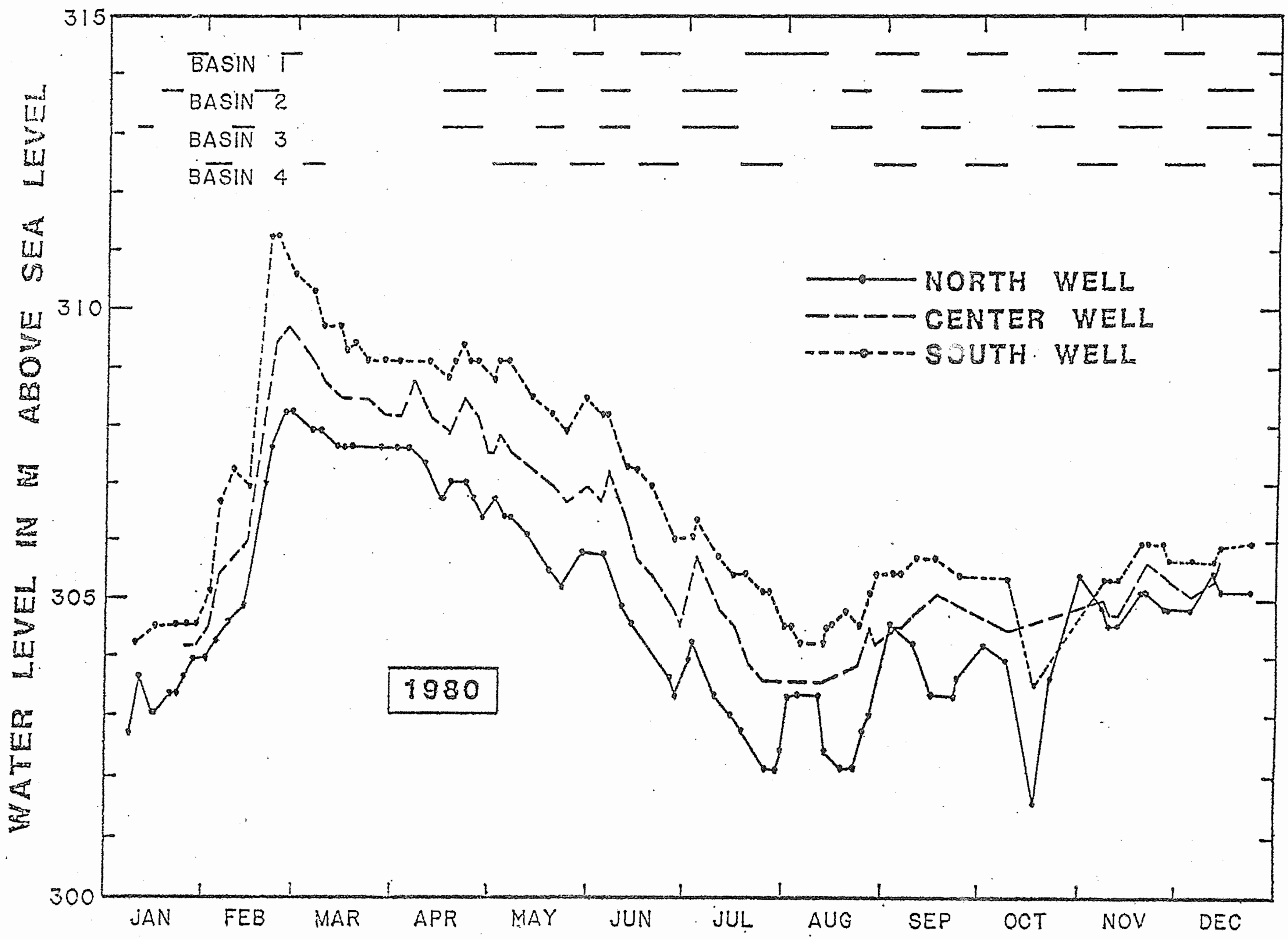

Figure 6. Water level elevations in the North, Center, and South Wells.

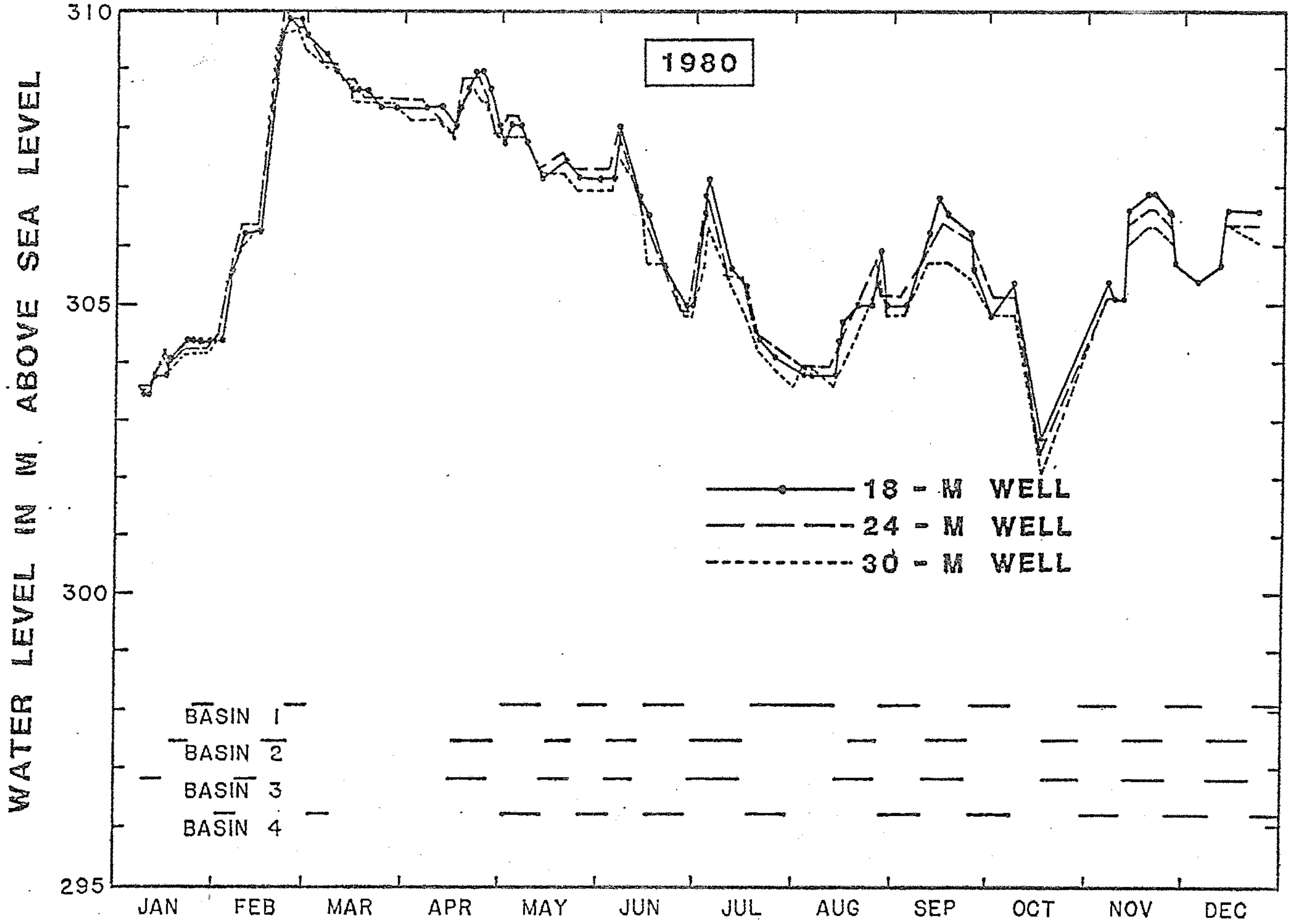

Figure 7. Water level elevations in the 18-m, 24-m, and 30-m Wells.

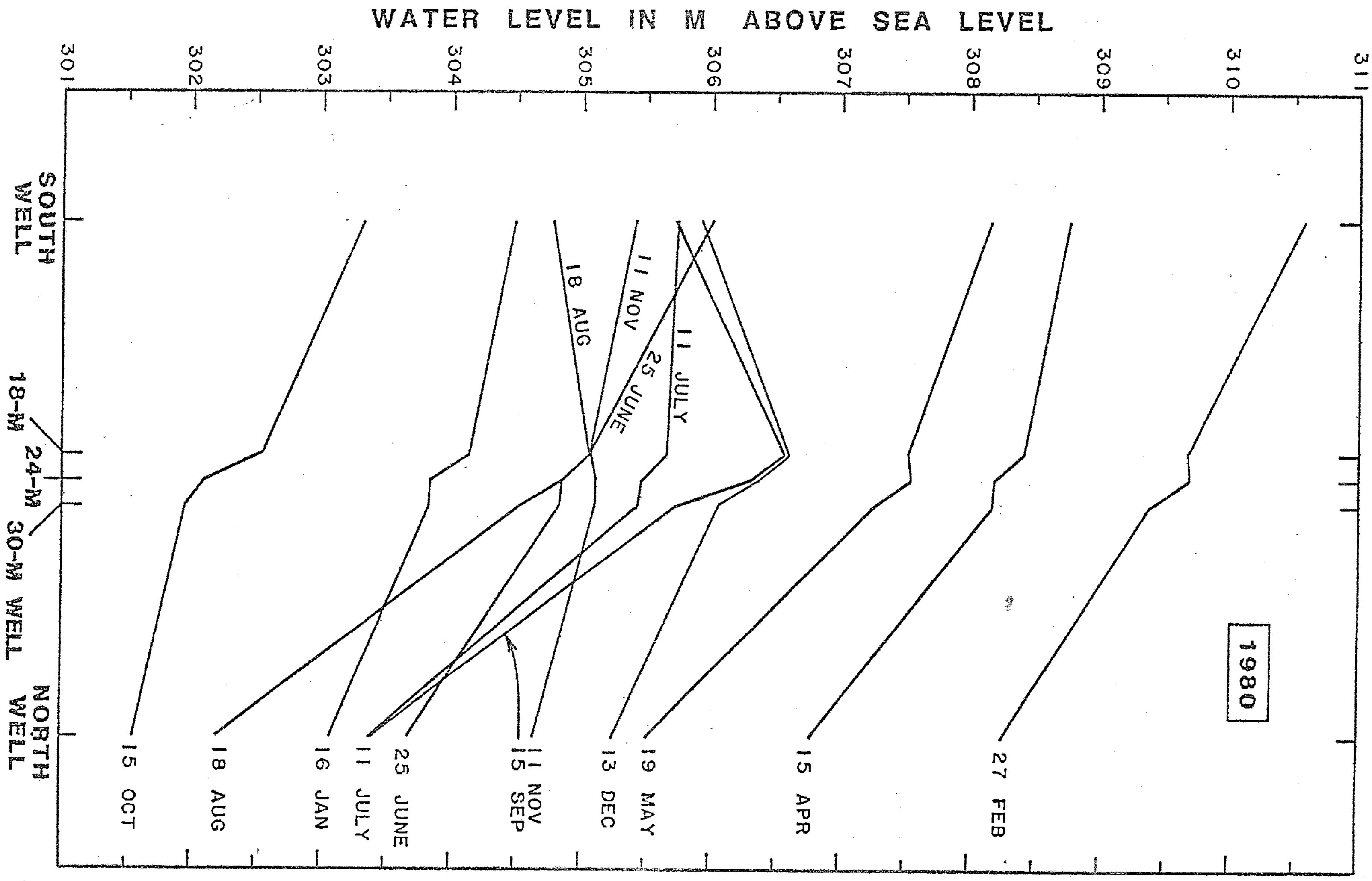

Figure 8. South-north groundwater level profiles below infiltration basins.

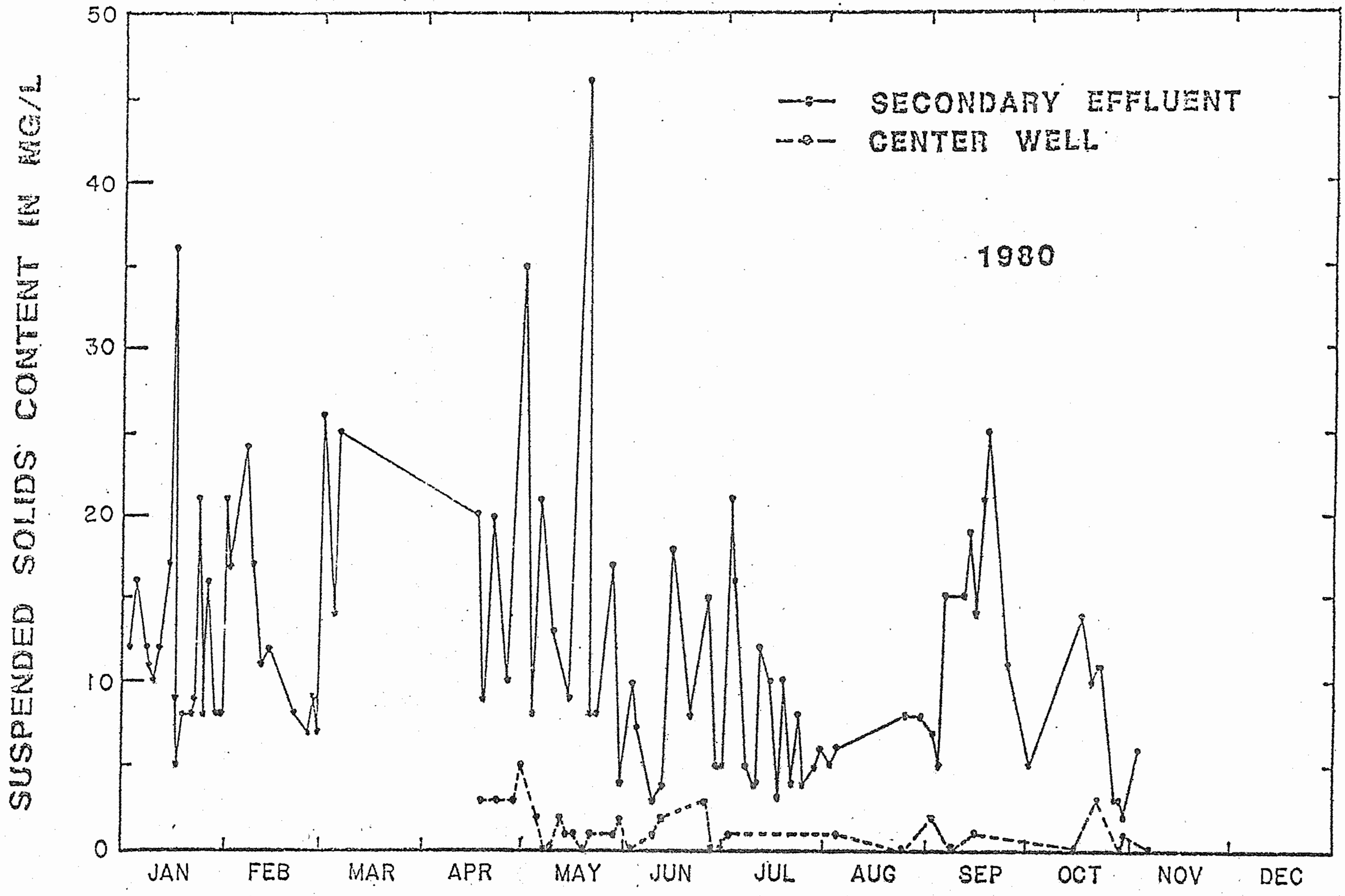

Figure 9. Suspended solids concentration in secondary effluent and renovated water from the Center Well.

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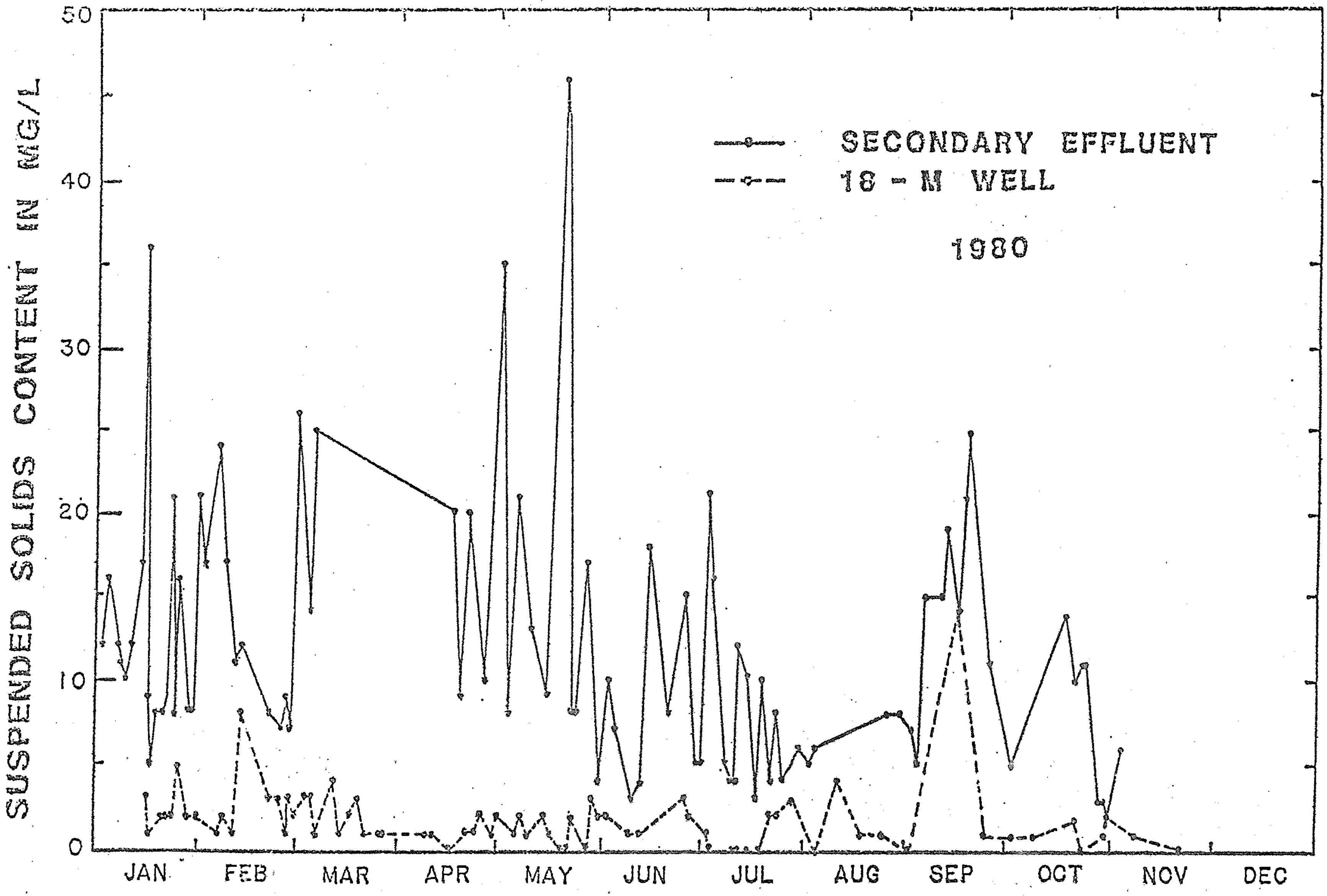

Figure 10. Suspended solids concentration in secondary effluent and renovated water from the 18-m Well.

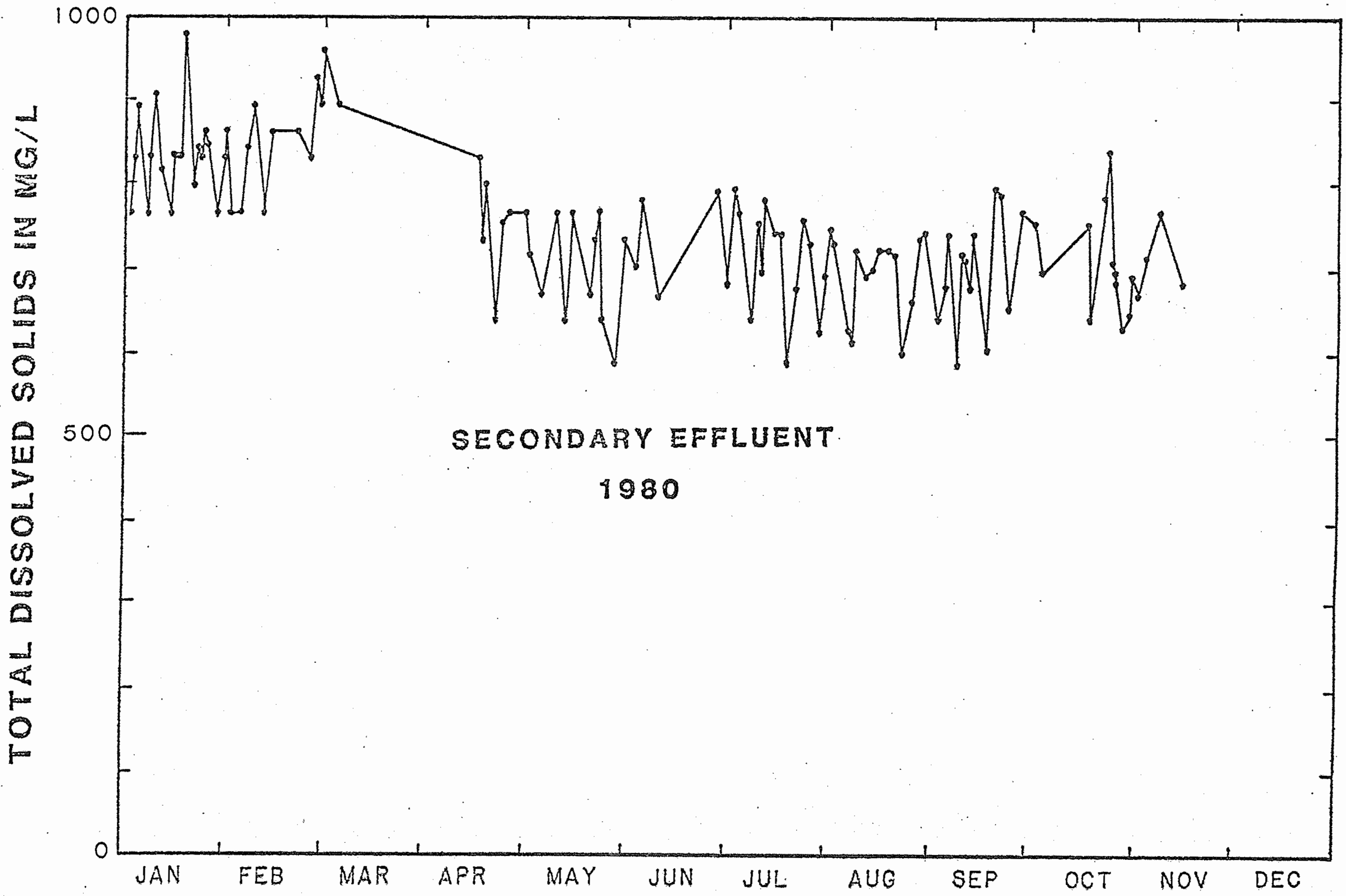

Figure 11. Total salt content in secondary sewage effluent.

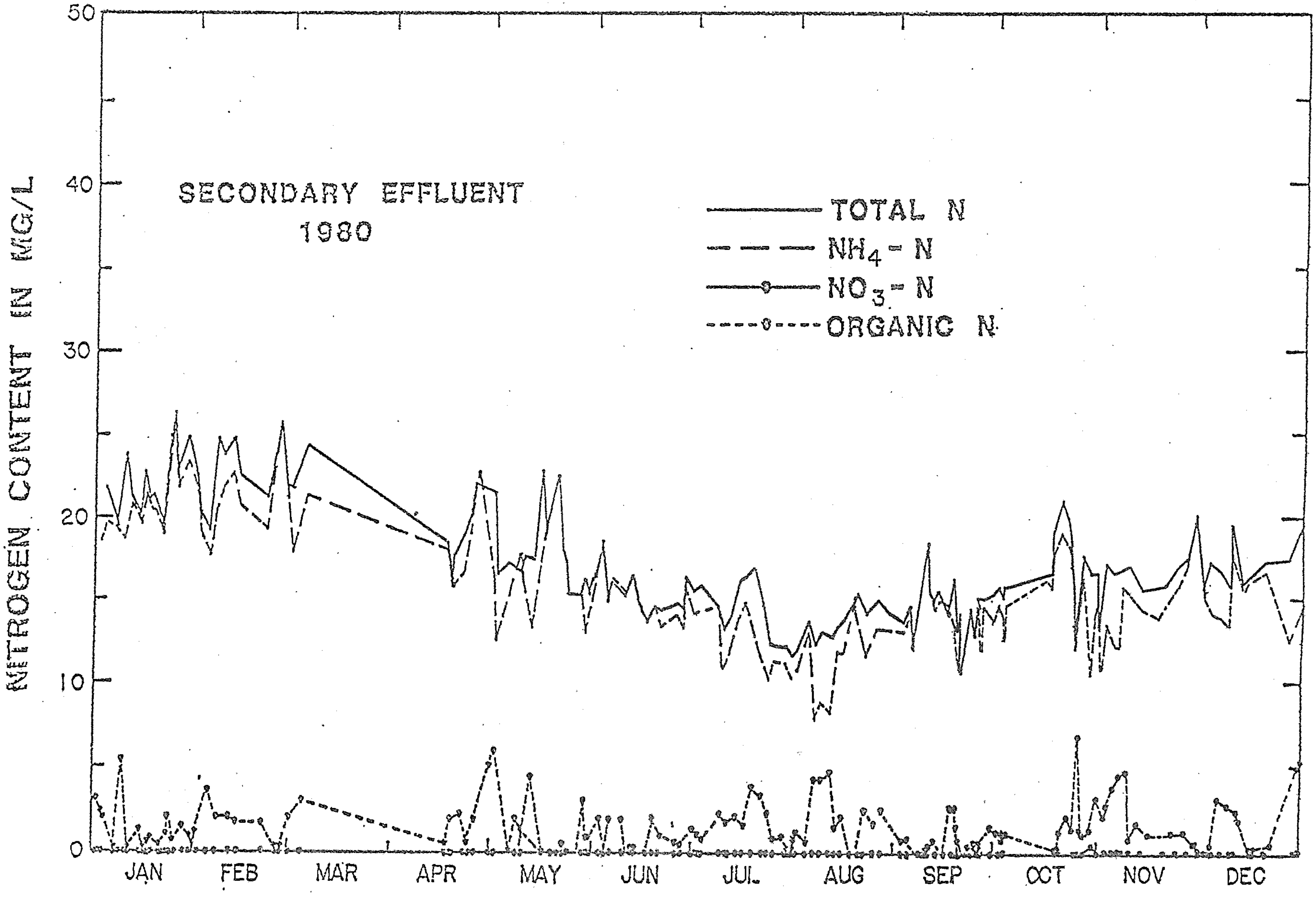

Figure 12. Nitrogen concentrations in secondary sewage effluent.

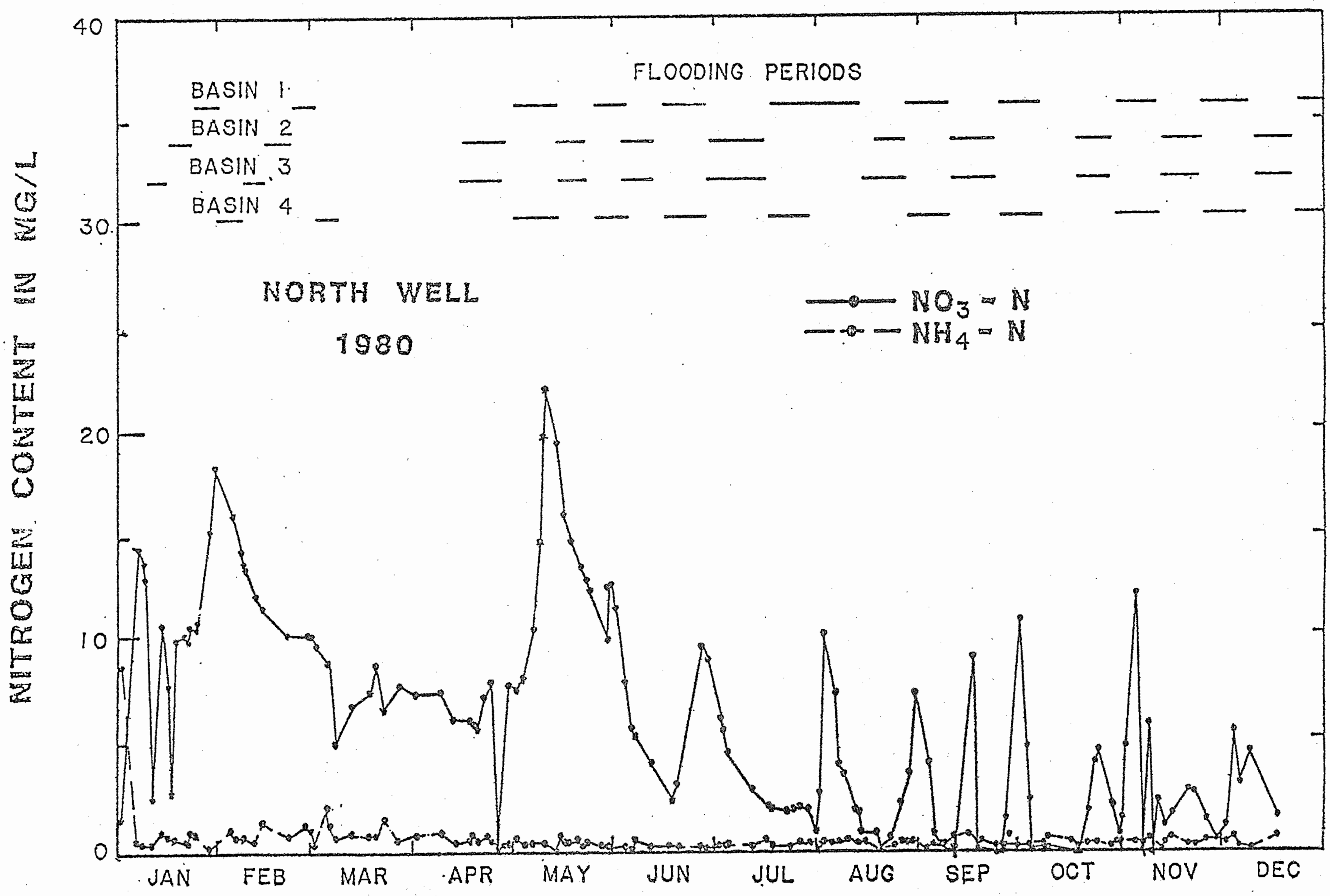

Figure 13. Nitrate and ammonium nitrogen concentrations in renovated water from the North Well.

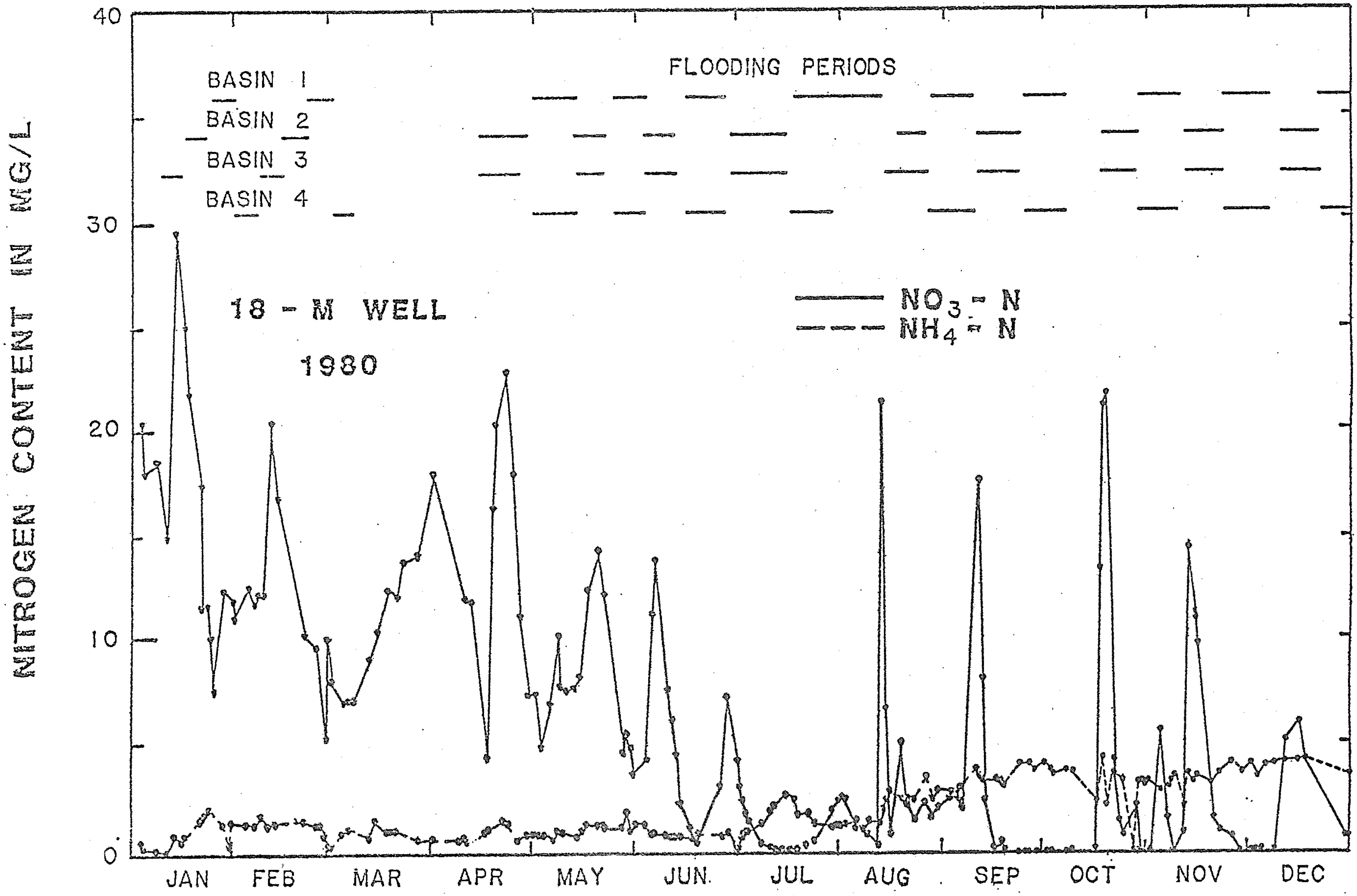

Figure 14. Nitrate and ammonium nitrogen concentrations in renovated water from the 18-m Well.

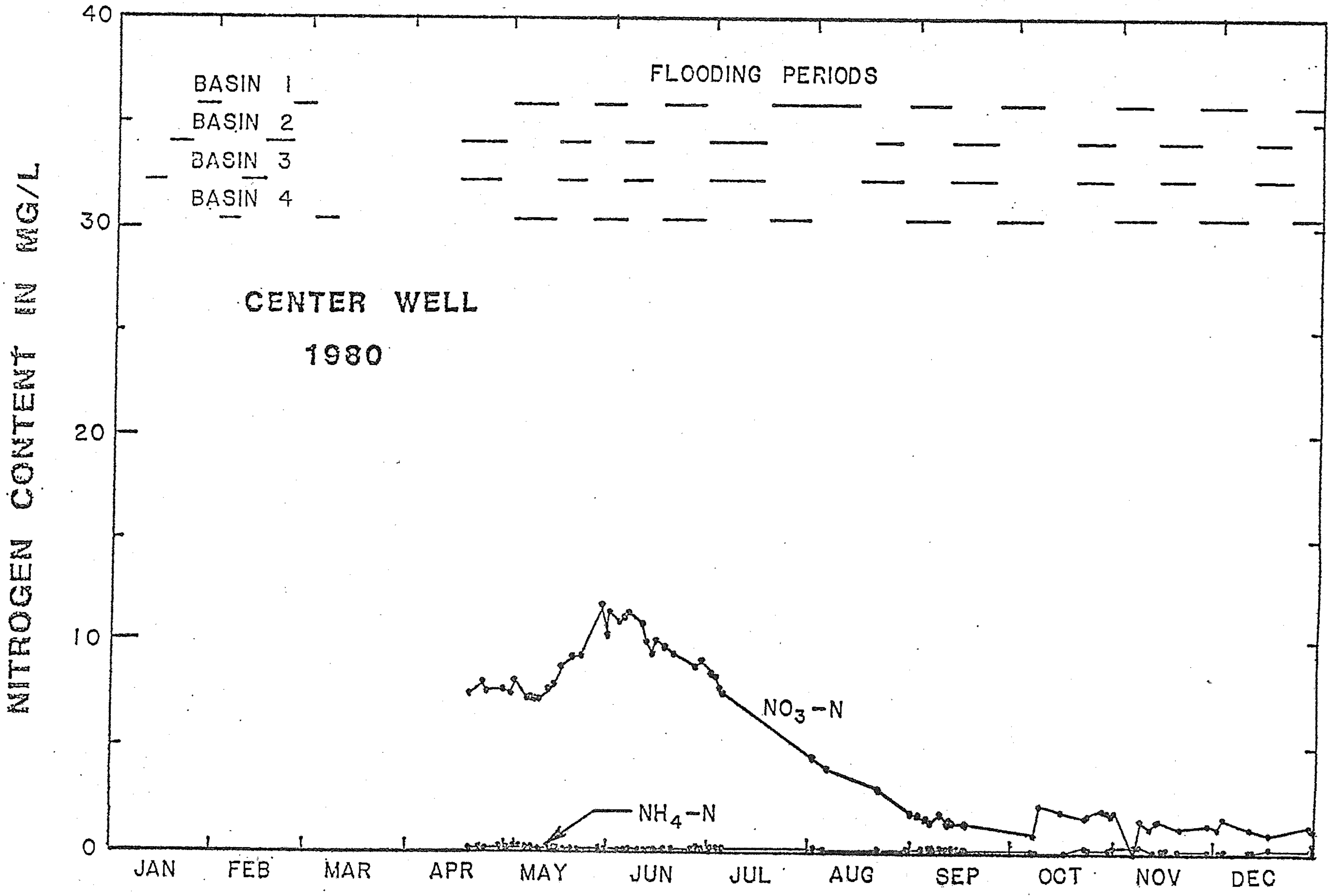

Figure 15. Nitrate and ammonium nitrogen concentrations in renovated water from the Center Well.

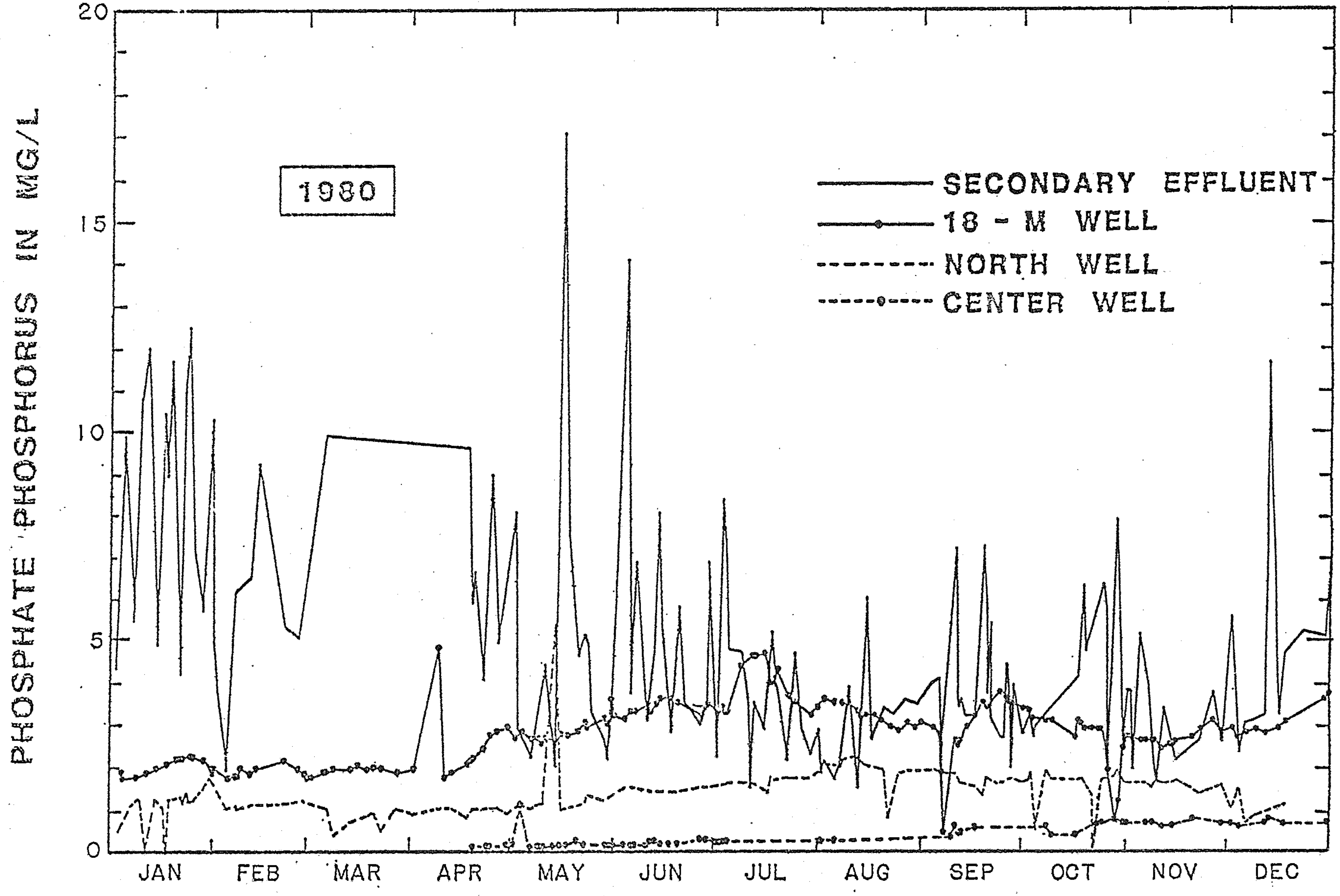

Figure 16. Phosphate phosphorus concentrations in secondary effluent and in renovated water from various wells.

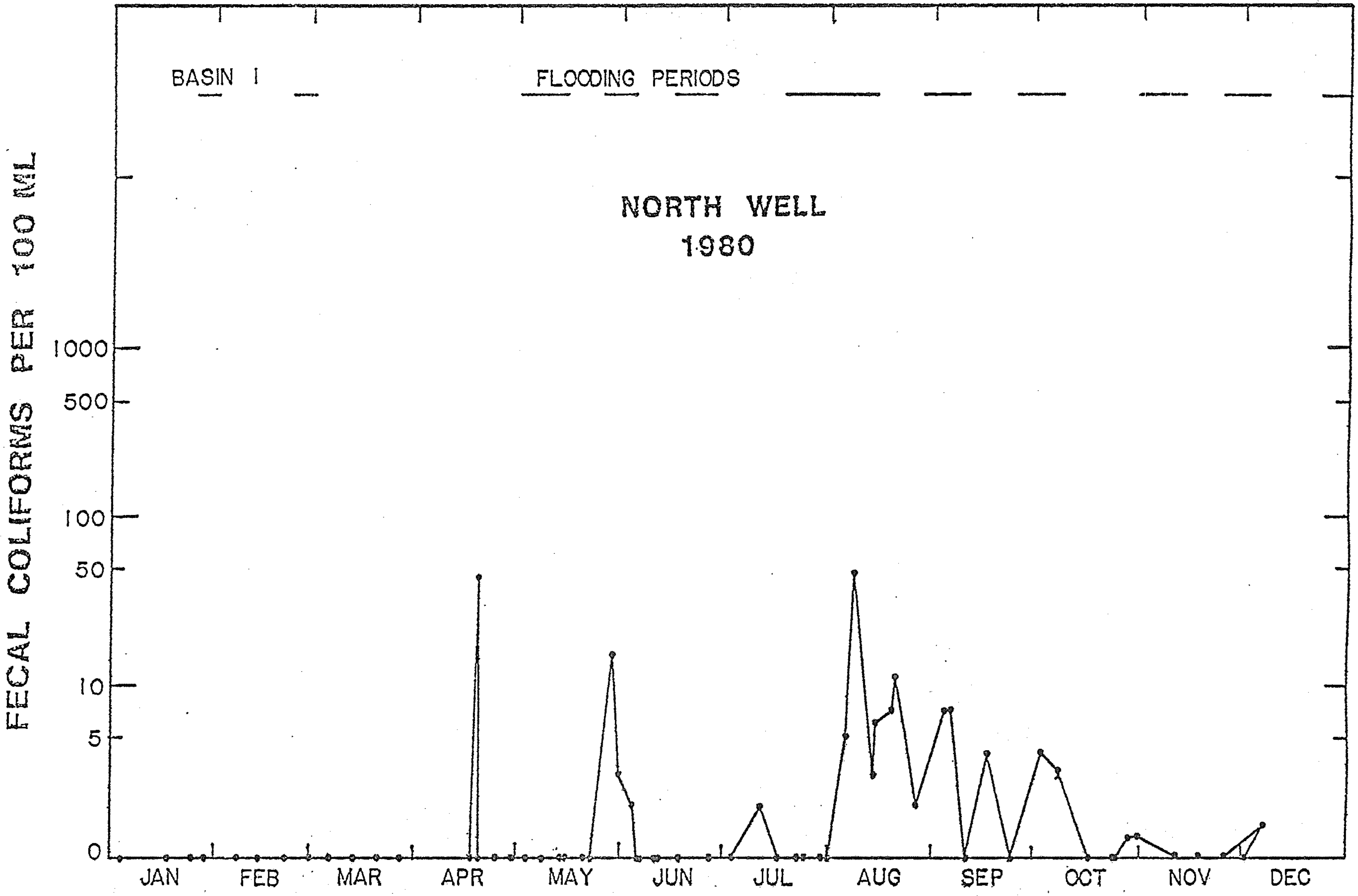

Figure 17. Fecal coliform concentrations in renovated water from North Well.

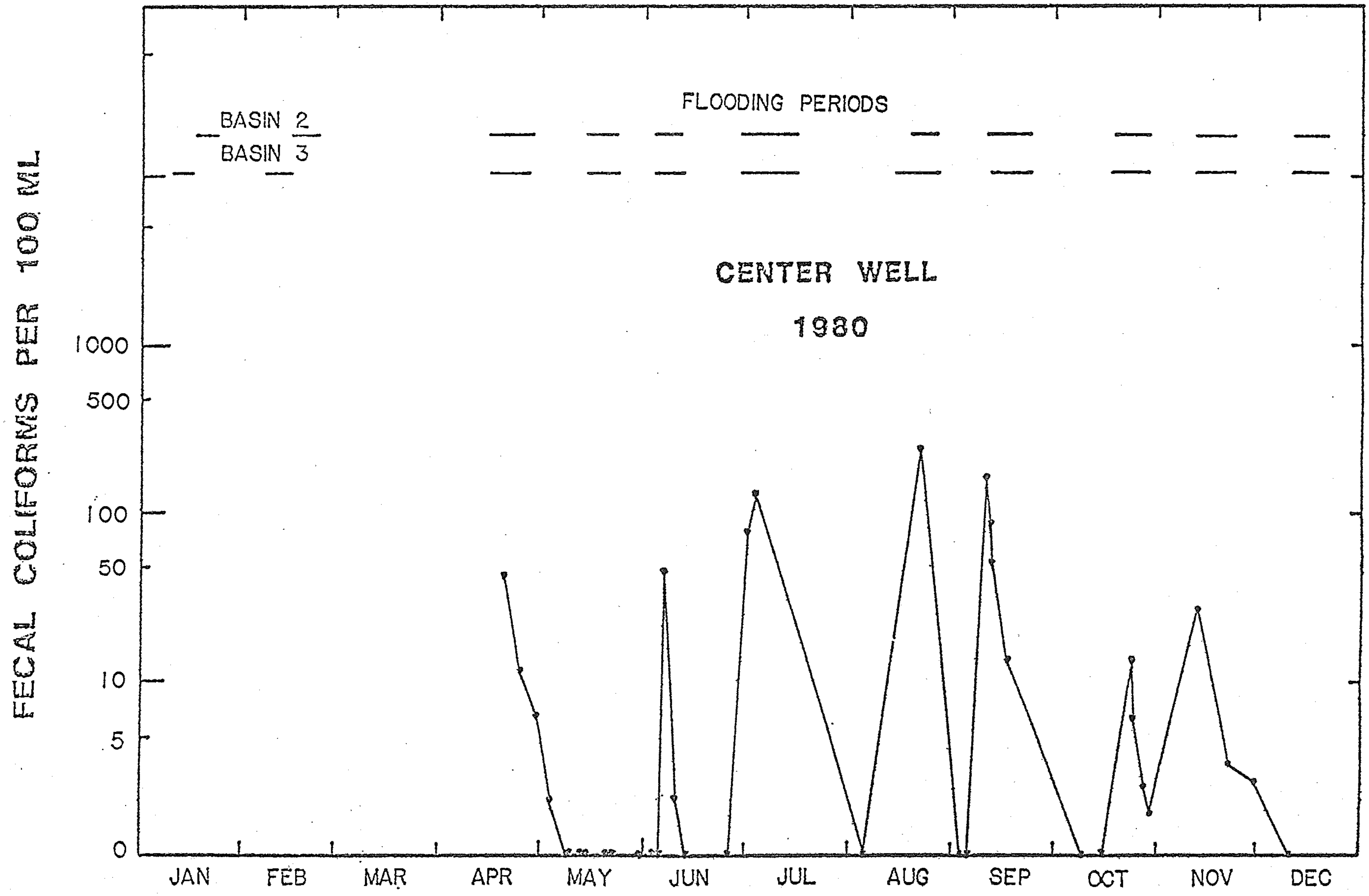

Figure 18. Fecal coliform concentrations in renovated water from Center Well.

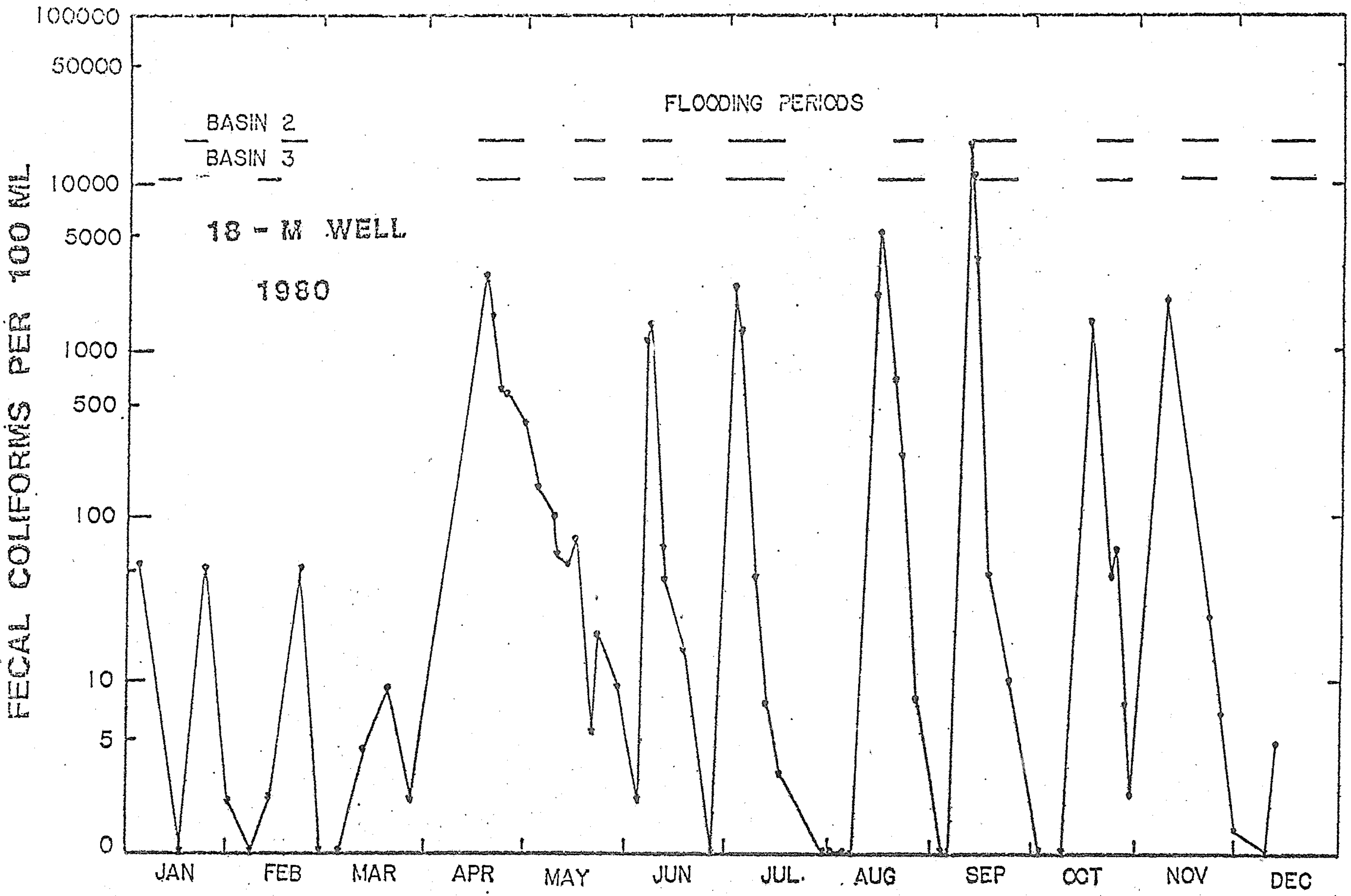

Figure 19. Fecal coliform concentrations in renovated water from 18-m Well.

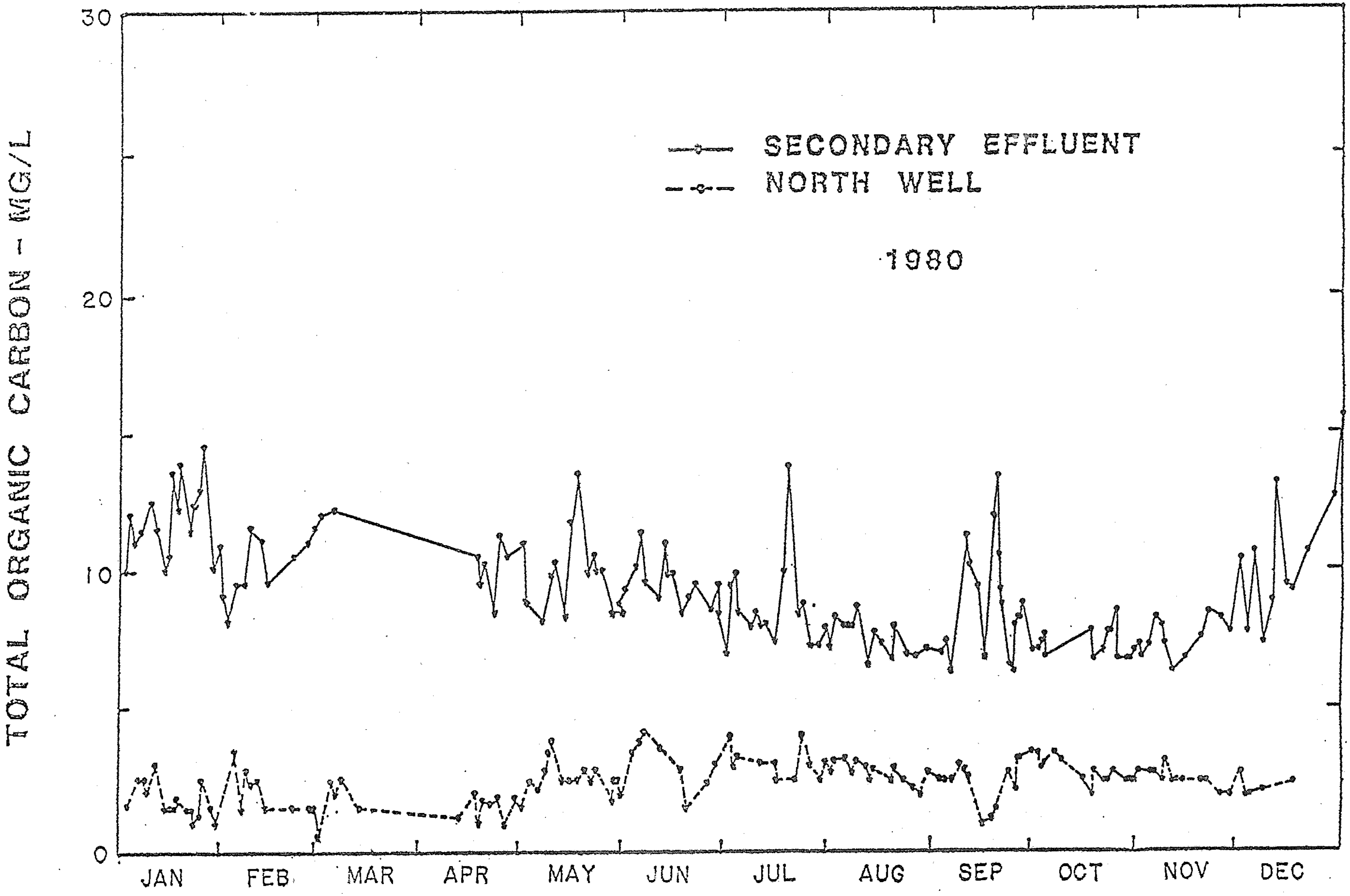

Figure 20. Total organic carbon concentrations in secondary effluent and in renovated water from North Well.

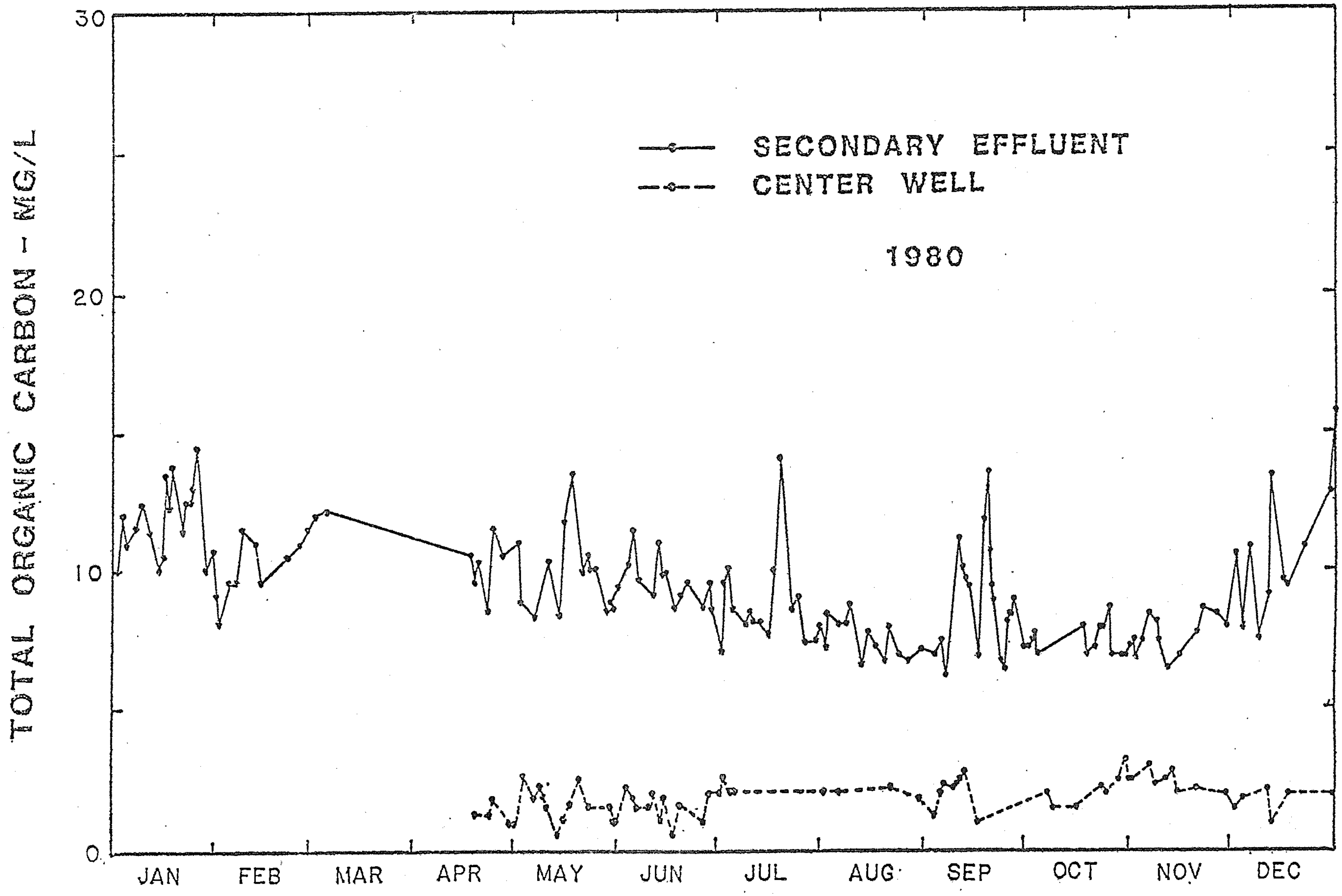

Figure 21. Total organic carbon concentrations in secondary effluent and in renovated water from Center Well.

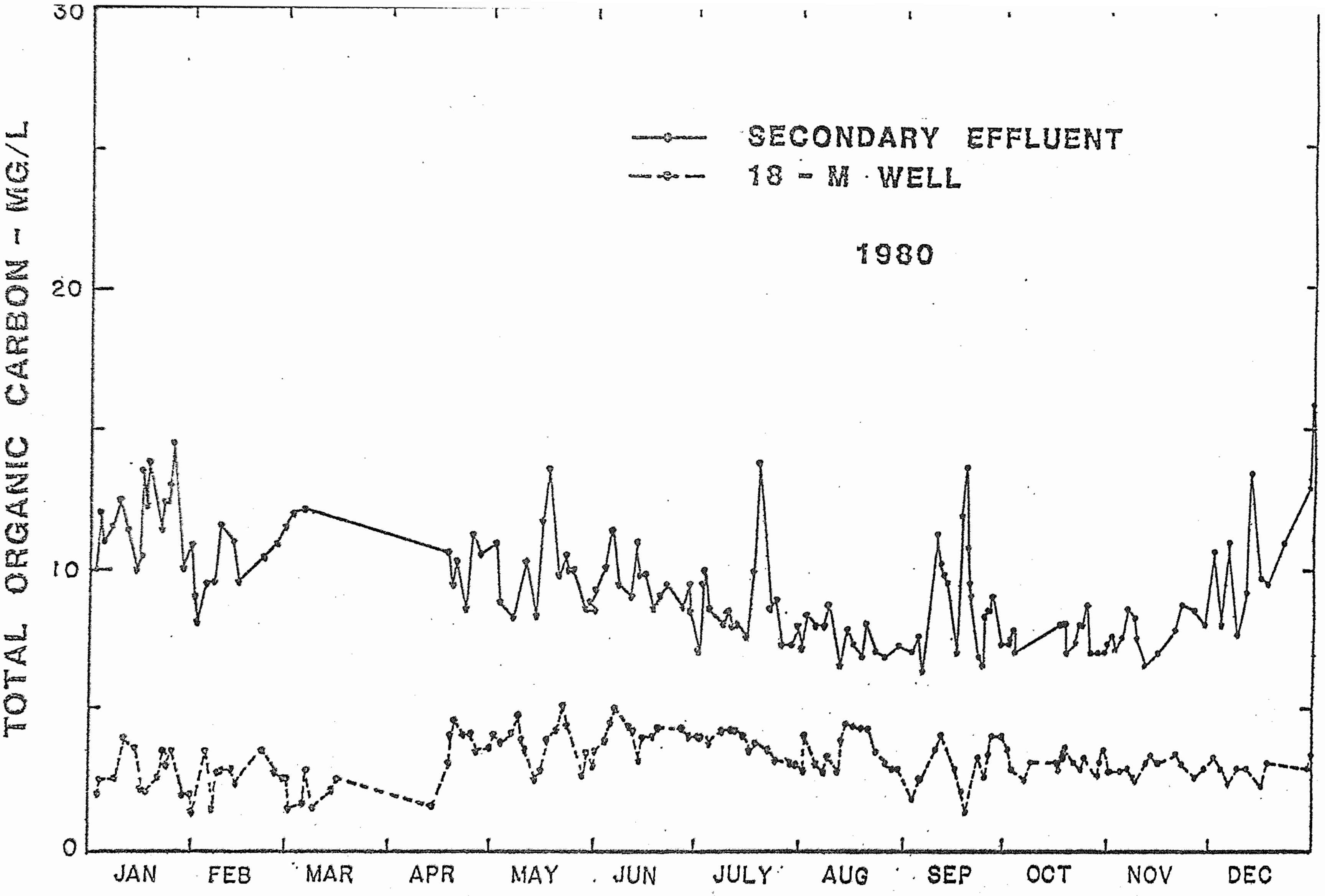

Figure 22. Total organic carbon concentrations in secondary effluent and in renovated water from 18-m Well.

TITLE: COLUMN STUDIES OF THE CHEMICAL, PHYSICAL AND BIOLOGICAL PROCESS OF WASTEWATER RENOVATION BY PERCOLATION THROUGH THE SOIL.

NRP: 20790 CRIS WORK UNIT: 5510-20790-004

INTRODUCTION:

Work on the effect of different salts on virus adsorption was continued during 1980. In addition virus movement during saturated and unsaturated flow was compared and the effect of sludge additions to the soil on virus movement was investigated. The addition of sludge to the surface layer of soil in the columns was tested as a method to increase denitrification. Cooperative projects at Baylor University on virus movement in different soils were continued.

PROCEDURE:

Salt effects on virus adsorption. To study the effect of different anions on virus adsorption, solutions of various salts were applied to the loamy sand column and samples were extracted for virus assay and for conductivity and Ca measurements as in previous studies. Each solution was applied for 3 days and one set of samples was extracted at the different depths on the second day of flooding and 2 sets on the third day. The following salts were used: $NaNO_3$-1mM, Na_2SO_4-1mM and 5mM, KH_2PO4-1mM and $CaNO_3$-2mM. Also, two other cations were used to complete the study on the effect of different cations. $AlCl_3$ was applied at 0.2 mM and NH_4Cl at 1 mM/1. Then $AlCl_3$ was added to sewage water at concentrations of 0.02, 0.1 and 0.5 mM/1 to determine if the effect of Al could be measured when organic compounds in the sewage water interfered with virus adsorption.

Virus movement during saturated and unsaturated flow. To study virus movement during unsaturated flow, sewage effluent seeded with poliovirus was metered onto the surface of the soil column using a peristaltic pump at the rate of 1.8 ml/min (32.5 cm/day). Soil water tension was measured with tensiometers at the 2, 20, and 40 cm depths. Samples were extracted for 3 consecutive days beginning on the 2nd day of flooding. Then the application rate was increased to 2.72 ml/min (49 cm/day) and the same sampling procedure was repeated. Then the column was flooded using a 10 cm head of water to provide essentially saturated flow. The column was sampled on 3 flooding days for virus assay. Then the overflow device at the bottom of the column was raised to a position level with the soil surface. The column was capped and a 87 cm head of water was applied using a tube connected to a jug elevated above the soil column. This procedure was used to assure complete saturation of the soil. Secondary effluent seeded with poliovirus was applied and the column was sampled on 3 flooding days. The infiltration rate was 38 cm/day. This flooding procedure was repeated using a 125 cm head to provide an infiltration rate of 54 cm/day and samples for virus assay were taken in a similar manner.

Effect of sludge on virus movement and nitrogen removed. Dry sludge was mixed in the top 5 cm of two soil columns at application rates equivalent to 50 mt/ha (40 g sludge added). The columns were flooded with sewage water on schedules of 9 days flooding alternated with 5 days dry. Viruses were seeded in the sewage effluent on the 6th day of the first flooding cycle and on the 8th day of the 4th cycle. Samples for virus assay were extracted on the 7th and 8th days of the first cycle and on the 9th day of the 4th cycle. Sludge was mixed in the top 10 cm of another column at the rate of 250 mt/ha (200 g sludge added). The column was flooded with sewage water on a 9 day flooding and 5 days drying schedule. The sewage was seeded with virus on the 6th and 7th days of cycle 1 and on the 7th and 8th days of cycle 2. Three sets of samples for virus assay were taken during cycle 1 and 2 sets during cycle 2. The outflow from all three columns was sampled daily for nitrogen, phosphate and organic carbon analyses. Periodically samples for organic carbon analyses were extracted at various depths.

RESULTS AND DISCUSSION:

Salt effects on virus adsorption. The maximum penetration depth was proportional to the ionic strength of the solutions of various anions (Fig. 1). However, the curve was different than the one for chloride salts (Fig. 2). Nitrates, sulfates, and phosphates were more effective than chlorides in promoting virus adsorption. Tap water was more effective than chlorides but less effective than the other salts because it is a mixture of all of these salts. Virus adsorption from secondary sewage effluent was similar to that from chloride salts. Apparently the positive effect of the nitrate, sulfate, etc. in sewage water on virus adsorption was about equal to the negative affect of organic compounds.

Aluminum and ammonium were more effective than cations tested previously in promoting virus adsorption (Fig. 3). Viruses applied in 0.2 mM $AlCl_3$ solutions did not penetrate below 20 cm in the soil column. When 0.1 mM $AlCl_3$ was added to secondary sewage effluent viruses did not penetrate below 40 cm. Therefore the effect of aluminum was slightly less in sewage water due to the organic content of sewage and to the precipitation of aluminum as aluminum phosphate, but it still increased virus adsorption considerably. Increasing the aluminum concentration to 0.5 mM had little additional effect. Adding 0.02 mMAl to sewage water had little effect on virus adsorption probably because most of the aluminum was precipitated as aluminum phosphate. Flocs could be easily seen when 0.5 mM aluminum was added but were not noticeable at lower aluminum concentrations. These data indicate that it may be practical to add small concentrations of aluminum salts to sewage water to prevent virus movement through porous soils with high infiltration rates. Another experiment to determine if virus movement through the coarse sand column at an infiltration rate of 4.5 m/day could be prevented by addition of aluminum to sewage has been conducted but the samples have not been analyzed at Baylor.

NH_4Cl solutions were also effective in promoting virus adsorption (Fig. 4). Both KNO_3 and NH_4Cl were much more effective than KCl because virus penetration with both solutions was limited to 20 cm as compared to 240 cm with KCl. Apparently ions which are radicals are more effective than ions composed of single atoms in promoting virus adsorption.

Virus movement during saturated and unsaturated flow. Virus movement during unsaturated flow was much less than during saturated flow (Fig. 5). The virus penetration depth at one-third and one-half the maximum flow rates were about the same although the results were slightly erratic for the lower flow rate (Table 1). The maximum penetration depth was 40 cm as compared to the usual depth of 160 cm with the column under saturated flow.

The tensiometers showed that the column was essentially saturated when it was operated with the usual 10 cm head and continuously flooded. Raising the column outlet to the top of the column and using a higher head of 87 or 125 cm made certain that the columns were completely saturated but had little or no additonal effect on virus adsorption (Table 2). The different flow rates also seemed to have little effect on virus adsorption. These results show that very little virus movement would be expected in soils where cropland is irrigated with sewage water because most of the soil water movement would be by unsaturated flow. Movement in septic tank fields would also be primarily by unsaturated flow and virus movement should be limited there also.

Effect of sludge on virus movement and nitrogen removal. Mixing sludge into the soil surface seemed to reduce virus adsorption near the surface but virus penetration was only slghtly increased (Tables 3 and 4). The higher application rate did not appear to increase virus penetration. However, more virus movement might have been measured if samples had been taken during the first day of the flooding cycle when carbon concentrations were at a maximum. The increased virus movement probably was due to interference by the organic carbon from the sludge.

Nitrogen removal by column 8 flooded with secondary sewage effluent at an infiltration rate of 30 cm/day was increased from about 25% to about 55% by incorporating dried sludge in the top 5 cm of soil at the rate of 40 mt/ha (Fig. 6). Incorporating the same amount of sludge in a column 2 with an infiltration rate of 60 cm/day decreased the nitrogen removal for several cycles before the nitrogen removal stablized at 34% which was about double the initial rate. Infiltration rates were not affected by incorporation of sludge. Incorporation of sludge at the rate of 200 mt/ha into the top 10 cm of column 5 that was flooded with sewage water at the rate of 75 cm/day resulted in about a 50% increase in the output of nitrogen from the column (Table 5). This persisted for 8 cycles or until the end of the year.

The combination of high infiltration rates and high sludge application rates probably caused the nitrogen output from the column. The dip in the nitrogen removal for cycles 6-11 for the columns with the 40 mt/ha sludge rate probably was due to nitrogen from the decomposing sludge. The column with the 30 cm/day flow rate allowed sufficient detention time and mixing for denitrification of most of the nitrate whereas much of it moved through the 60 cm/day column. Therefore these columns demonstrated again that denitrification is governed by a combination of factors including infiltration rate, C:N ratio, and detention time. Sludge decomposition rates would differ in the field but the columns indicate that sludge addition would increase N removal. Incorporation of sludge into the soil did increase the organic carbon content of the water at various depths (Tables 6 and 7). These results suggest that mixing sludge in the surface soil of groundwater recharge basins would increase the N removal rate thereby increasing the rate at which wastewater could be applied and decreasing the cost of the renovated water.

Some phosphate was released from the sludge mixture during the first flooding cycle and peaked after 3 cycles (Figures 7 and 8). The phosphate output then decreased with output equivalent to the average presludge concentration after five cycles. By the end of the year the phosphate concentrations in water were about the same as those in the incoming sewage.

SUMMARY AND CONCLUSION:

Nitrate, sulfate and phosphate salts were more effective than chloride salts in promoting virus adsorption. Also aluminum and ammonium were more effective than other cations in stimulating virus adsorption. Aluminum chloride solutions as low as 0.1 mM in sewage water limited virus penetration to the top 40 cm of soil. This information will be helpful in predicting virus movement through different soils when various kinds of wastewater are applied. These studies also suggest that it may be practical to add very low concentrations of some salts such as aluminum sulfate to sewage if needed to limit the movement of viruses through very porous soils. When poliovirus and fecal coliform concentrations were measured in the same samples from different depths, virus movement through the soil column roughly paralleled coliform movement. Movement of viruses during unsaturated flow of sewage through soil columns was much less than during saturated flow. Viruses did not move below the 40 cm level when sewage water was applied at less than the maximum infiltration rate while virus penetration in columns flooded with sewage was at least 160 cm. Nitrogen removal by a column flooded with secondary sewage effluent at an infiltration rate of 30 cm/day was increased from about 25% to about 55% by incorporating dried sludge into the top 5 cm of soil at 40 mt/ha rate. These results suggest that mixing sludge into the surface soil of groundwater recharge basins would increase the N removal rate thereby allowing a higher wastewater application rate and decreasing the cost of the renovated water.

PERSONNEL: J. C. Lance, G. C. Auer

Table 1. Virus removed from sewage water by a soil column during unsaturated flow.

Column Depth (cm)	Flow Rate - cm/day 32.5	49	Average
		Percent viruses remaining	
2	12.4	10.9	11.7
10	0.02	0.9	0.5
20	0.	0.2	0.1
40	0.09	0	0.05
80	0	0	0
160	0	0	0
240	0	0	0
250	0	0	0

Table 2. Virus removal from sewage water by a soil column during saturated flow.

Column depth (cm)	Flow Rate - cm/day* 38	54	100	Average
	Percent viruses remaining			
2	61.9	12.5	62.5	45.6
5	20.5	11.5	15.3	15.3
10	8.2	6.6	6.0	6.9
20	5.9	4.5	3.3	4.6
40	3.4	2.7	1.0	2.4
80	2.0	3.6	0.3	2.0
100	0.03	0.04	0	0.02
240	0	0.02	0	0.007
250	0	0	0	0

* Flow is almost saturated under normal flooding with 10 cm head; First two rates are with outflow device raised to the top of the column and heads of 87 and 125 cm.

Table 3. Virus concentrations at various depths in column treated with 50 mt/ha of sludge.

DEPTH (cm)	COLUMN 2 Day 7*	COLUMN 1 Day 7	COLUMN 1 Day 8	COLUMN 2 Day 9	COLUMN 2 Day 9.3
		PFU/ml			
0	4000	1200	1100	5,500	4,000
2	1950	190	300	7100	11000
5	1200	50	200	2850	2650
10	1025	375	120	3550	570
20	240	20	45	405	75
40	110	210	65	550	70
80	45	220	30	75	40
160	25	5	30	10	0
240	0	0	10	5	0
250	5	–	10	5	10

* Indicates 7th day of 9 day flooding cycle.

Table 4. Virus concentrations in a column treated with 250 mt/ha of sludge.

Depth (cm)	CYCLE 1			CYCLE 2	
	Day 7	Day 8	Day 8.5	Day 8	Day 9
0	3525	1050	2700	6950	5450
2	2000	2235	3450	1100	1350
5	–	3650	4300	850	1215
10	550	170	3150	105	240
20	140	250	5150	15	255
40	120	85	30	20	40
80	20	45	45	0	10
160	15	10	0	0	15
220	5	0	0	0	5
250	10	0	0	0	15

Table 5. Nitrogen removal rates of columns treated with sludge. (Sludge added on 4/15 to Columns 2 and 8, and on 7/22 to Column 5)

	N Removal (%)		
Cycle Date	Column 2	Column 5	Column 8
3/12 - 3/27	21.9		19.3
3/27 - 4/15	11.6		24.5
4/15 - 4/29	21.9		21.7
4/29 - 5/14	32.5*		19.1*
5/14 - 5/28	47.3		44.5
5/28 - 6/11	33.2		61.6
6/11 - 6.25	10.4		50.5
6.25 - 7.7	14.8		57.4
7/9 - 7/23	5.8		45.4
7/23 - 8/6	17.6	-7.7	22.8*
8/6 - 8/20	1.3	-39.1	36.3
8.20 - 9/3	20.9	-104.7	56.5
9/3 - 9/17	34.7	-92.9	56.0
9/17 - 10/1	33.5	-20.7	53.5
10/1 - 10/15	33.6	-55.3	58.4
10/15 - 10/29	22.6*	-25.9**	59.7
10/29 - 11/12	35.0	-62.0	50.2

* Columns dry over night
** Incomplete data

Table 6. Organic carbon concentrations at various depths and dates in 2 columns treated with 50 mt/ha sludge on 4/15/80*.

Depth (cm)	Organic Carbon On: 4-16-81 Col.2	4-16-81 Col.8	4-21-81 Col.2	4-21-81 Col.8	4-23-81 Col.2	4-23-81 Col.8	4-30-81 Col.2	4-30-81 Col.8
	mg/l							
0	8.3	10.3	9.0	12.0	7.2	7.0	9.0	13.0
2	11.3	12.0	7.5	9.0	8.7	8.0	11.5	10.2
5	19.0	24.0	11.0	27.5	9.1	11.0	13.0	16.0
10	17.5	36.0	12.5	16.5	11.0	11.8	16.0	19.5
20	16.0	31.0	12.0	13.7	9.8	12.5	13.0	19.0
40	15.8	36.5	10.0	13.0	11.3	11.3	10.0	12.8
80	13.0	44.0	11.5	14.0	8.8	11.4	8.0	8.0
160	15.8	11.0	9.5	9.0	8.0	9.8	10.0	8.5
240	17.8	6.4	7.5	8.5	6.8	6.8	10.8	7.0
250	20.0	5.0	11.5	7.0	5.8	5.5	6.0	4.8

* Columns were dried from 4/25 - 4/29

Table 7. Organic carbon concentrations at various depths in a column treated with 250 mt/ha sludge on 7/23/80 before flooding with sewage water.

Organic Carbon On:

Column depth (cm)	7-24(1)*	7-25(3)	7-29(6)	7-31(8)	8-8(2)	8-15(9)	8-21(1)	8-29(9)	9-4(1)	9-19(2)
0	10.5	8.8	8.5	7.8	7.2	6.6	8.2	-	8.5	6.2
2	21.0	16.0	12.5	10.7	13.0	7.0	11.6	-	8.5	6.1
5	43.0	30.0	20.0	12.0	10.3	8.0	10.0	-	10.5	6.4
10	69.0	37.5	25.5	21.0	17.3	12.0	16.0	13.4	13.2	18.5
20	96.0	52.5	25.5	22.8	16.0	12.0	14.5	10.6	11.5	7.0
40	145.0	54.0	19.3	16.8	13.8	10.2	13.0	10.0	11.0	7.3
80	283.0	60.0	20.0	14.2	13.8	10.0	10.5	9.3	10.5	7.0
160	1125.0	150.0	17.5	12.0	12.8	8.2	19.5	7.5	13.0	8.0
240	130.0	190.0	14.8	13.3	12.5	8.2	17.5	7.8	15.5	10.8
250	7.5	270.0	16.0	15.0	13.8	8.5	18.5	7.5	18.2	-

* indicates number of days after flooding cycle began

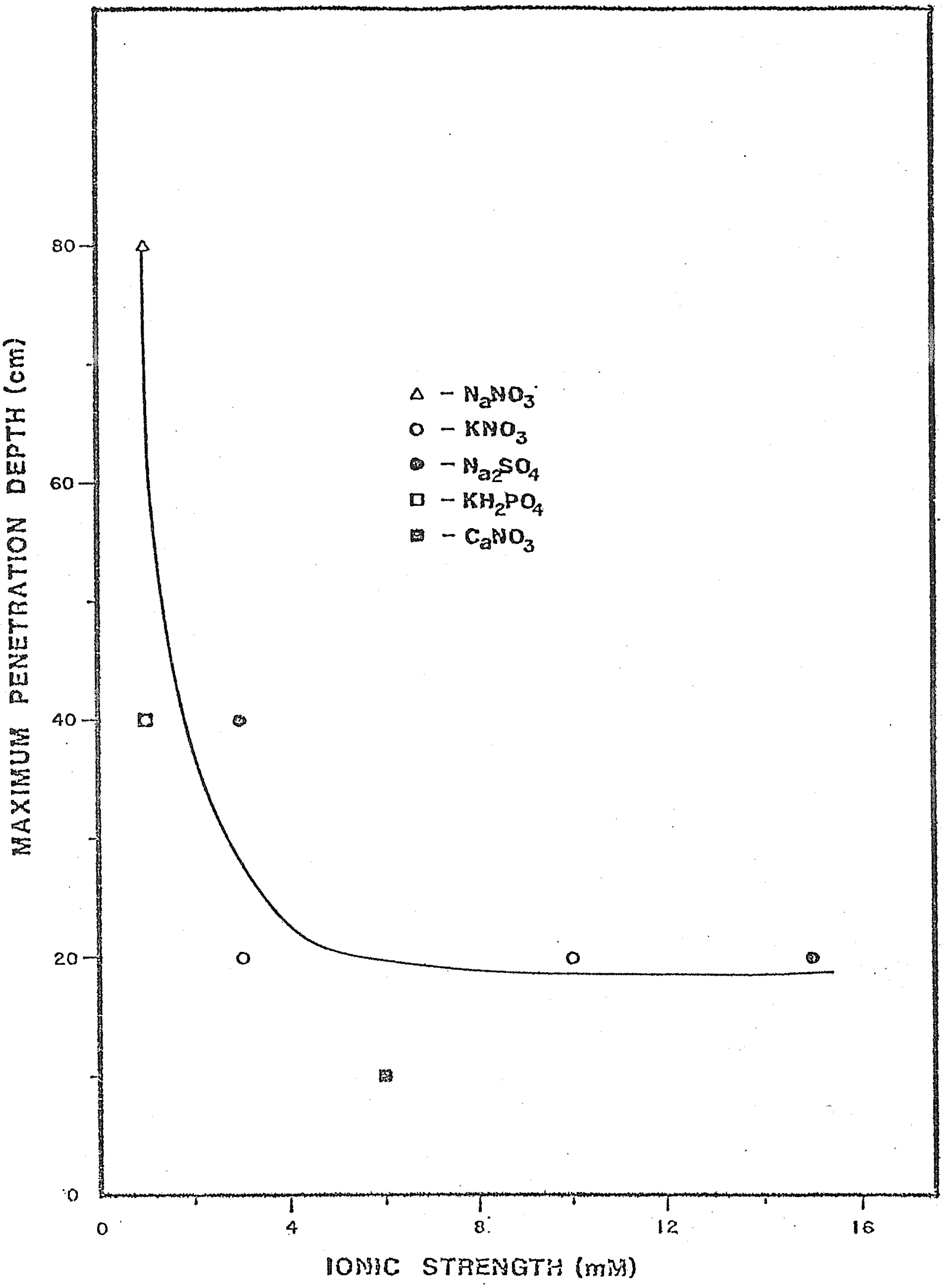

Figure 1. Effect of ionic strength of non-chloride solutions on the maximum depth of penetration by viruses in soil columns.

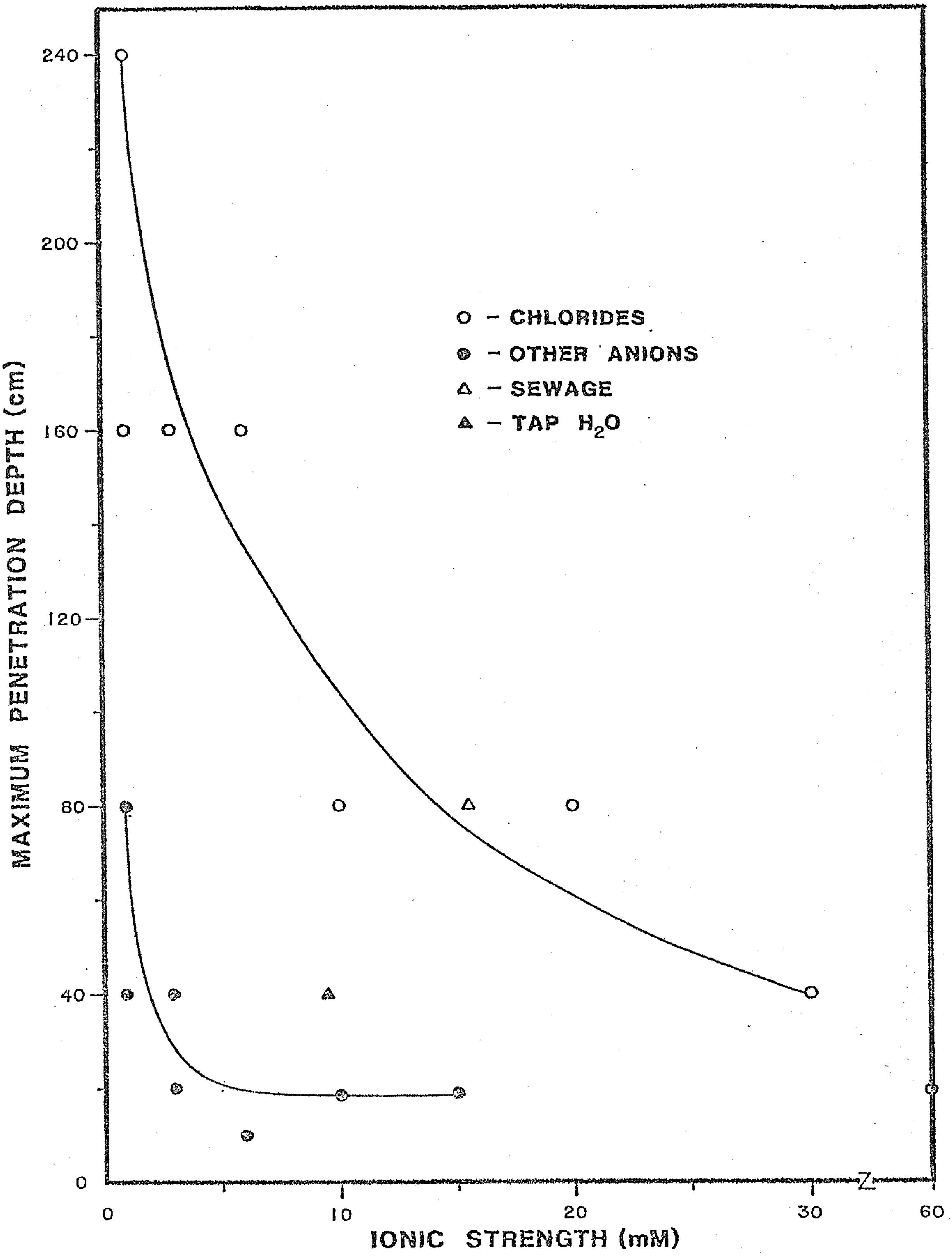

Figure 2. Effect of ionic strength of various solutions on the maximum depth of penetration of viruses in soil columns.

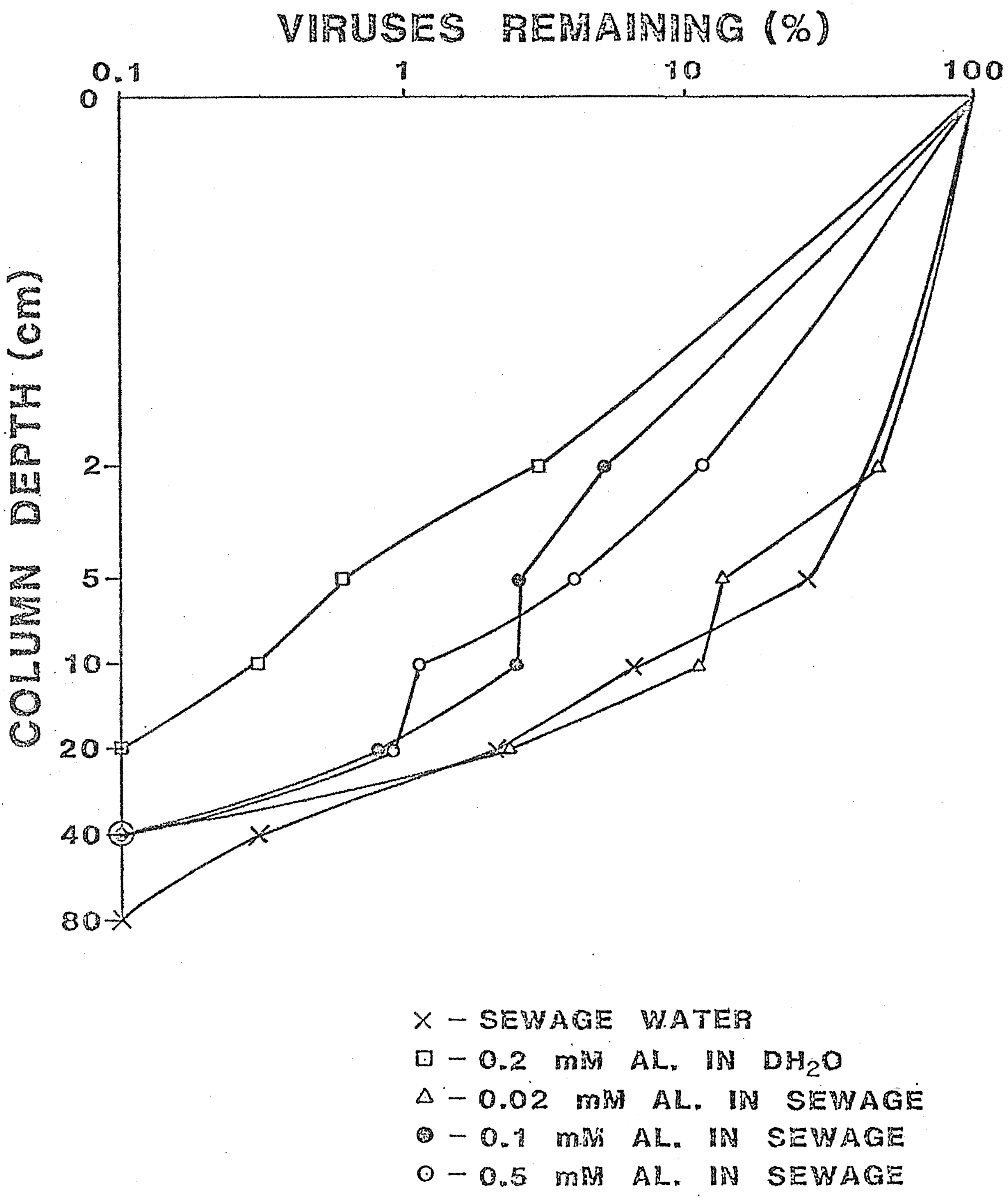

Figure 3. Virus adsorption by soil columns for various concentrations of Al salts.

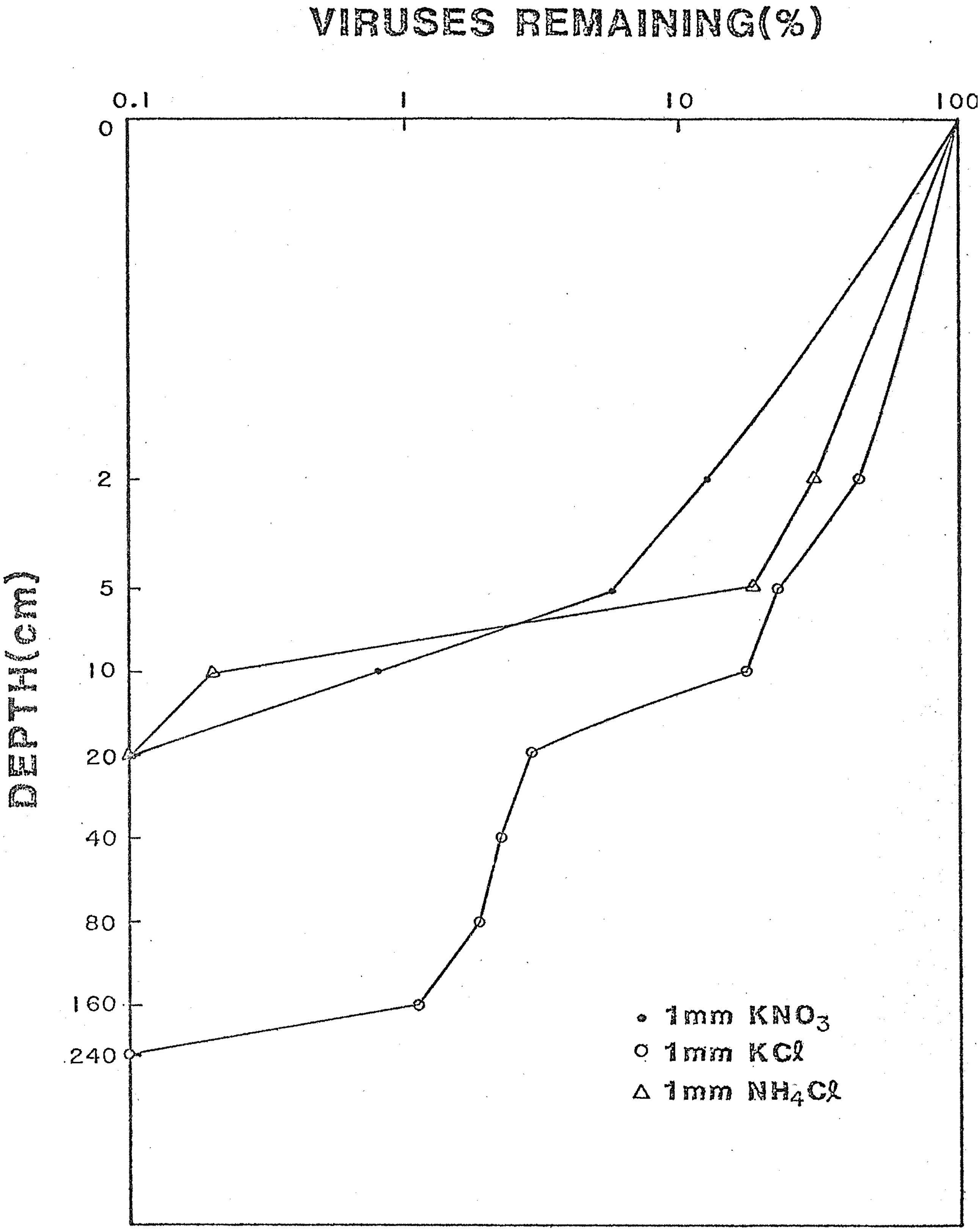

Figure 4. Virus adsorption of soil columns from solutions of KNO_3, KCl, and NH_4Cl.

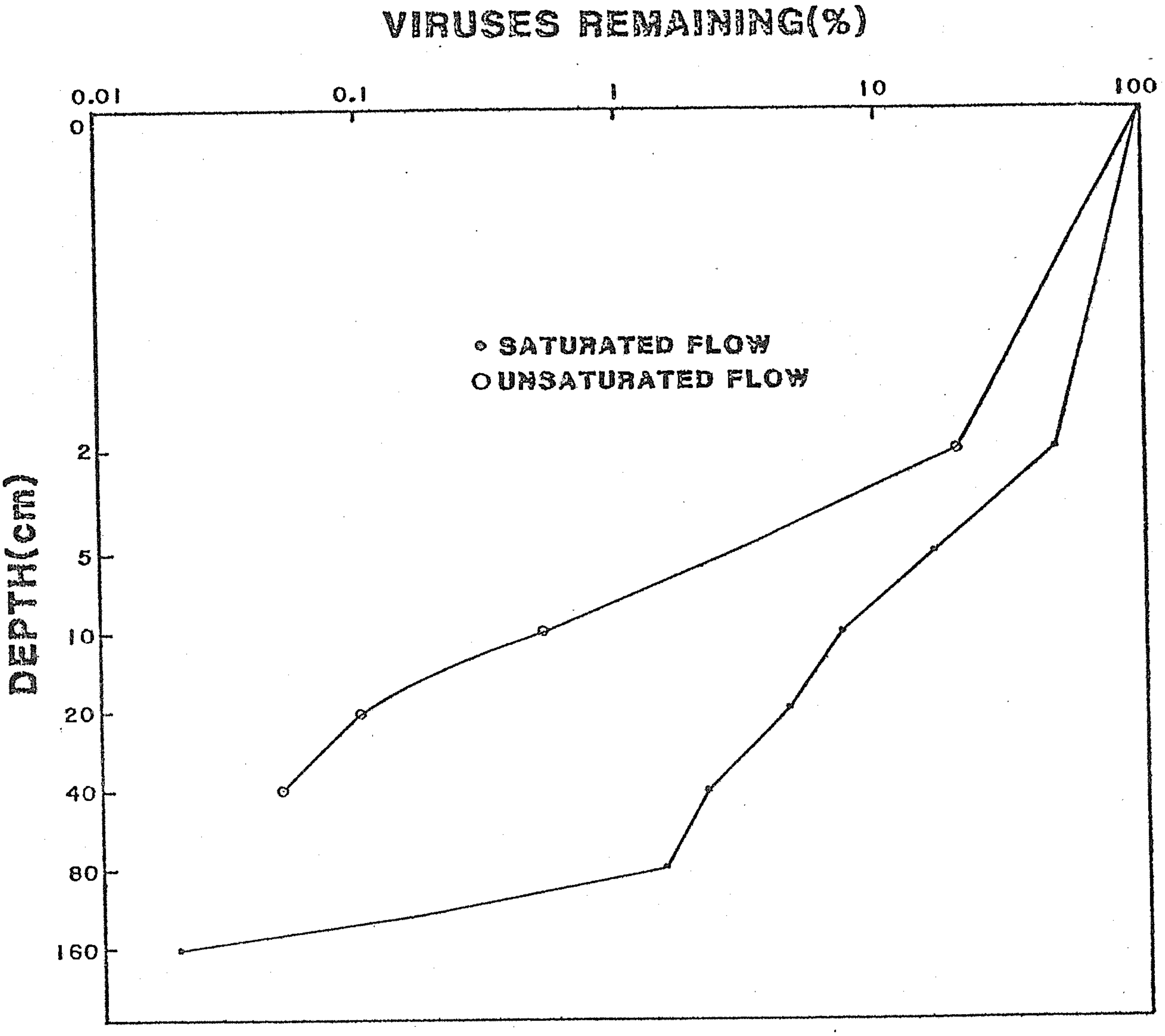

Figure 5. Virus adsorption of soil columns for saturated and unsaturated flow.

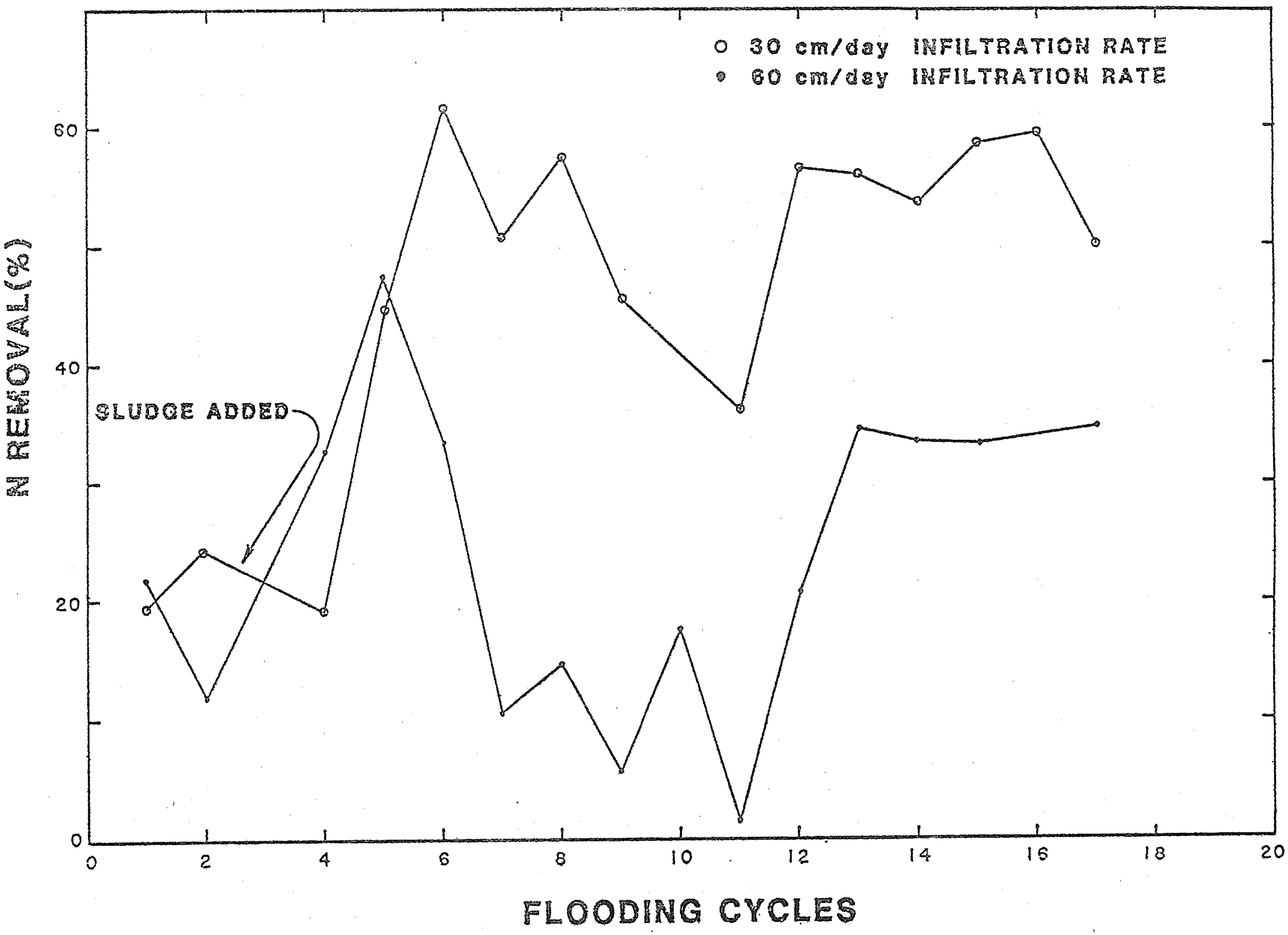

Figure 6. Nitrogen removal from soil columns amended with dry sludge.

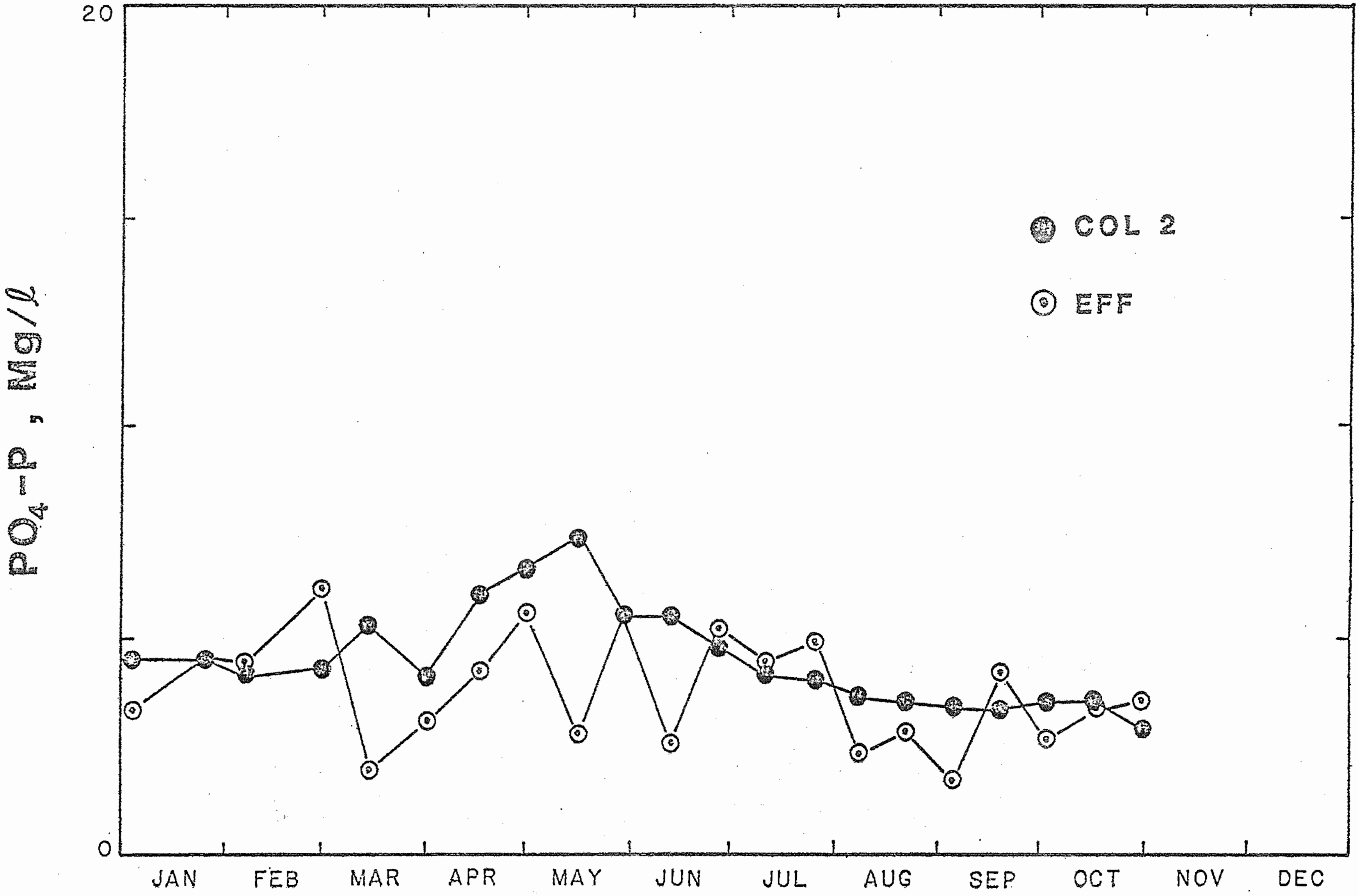

Figure 7. Average phosphate concentrations from column 2 with sludge added on 15 April.

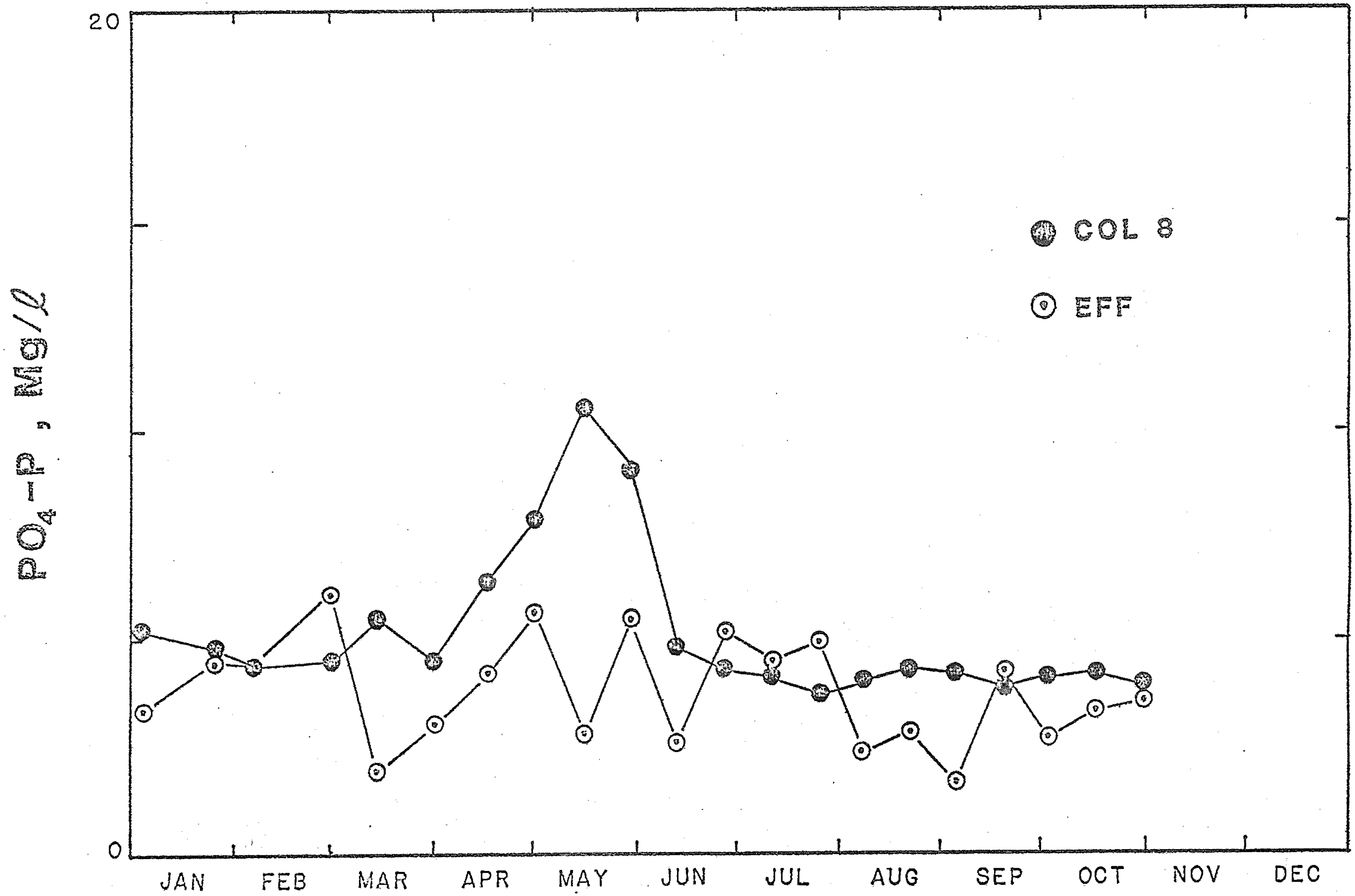

Figure 8. Average phosphate concentrations from column 8 with sludge added on 15 April.

TITLE: CHEMICAL MODIFICATION OF SOILS FOR HARVESTING PRECIPITATION

NRP: 20810 CRIS WORK UNIT: 5510-20810-004

LABORATORY STUDIES:

A number of accelerated weathering studies was initiated and/or completed, evaluating various types and combinations of soil stabilizers, repellents, and repellent-additives, on several soils with different physical-chemical-mineralogical properties.

Coupling (antistripping) agents were evaluated for strengthening the paraffin-soil interfacial bond under wet freeze-thaw cycle weathering. Eleven antistripping agents were evaluated. All improved paraffin weatherability, but several were outstandingly better than others. Soils treated with certain of the antistrip-paraffin mixtures were more than 10 times as resistant to freeze-thaw cycle weathering compared to the paraffin-only treatment. An effective soil treatment was obtained with only 0.5 kg/m^2 of paraffin containing 2% antistrip. This is one-fourth the currently recommended paraffin application rate on soils subjected to freeze-thaw cycling. Stabilization of the soil with cellulose xanthate, made from wastepaper, prior to treating with the paraffin-antistrip mixtures, permitted a further reduction in the application rate of wax to only one-eighth the currently recommended rate. Details will be published in Paraffin-Wax Water Harvesting Soil Treatment Improved With Antistripping Compounds (in progress).

Preliminary investigations had suggested that soils treated with certain residual type waxes could withstand more weathering than paraffin-treated soils. Twelve waxes as water-harvesting soil treatments were evaluated in the laboratory for wet freeze-thaw weatherability. There were large differences in performance, but in general, residual type waxes outperformed refined paraffins. Weatherability of all the waxes was markedly improved by adding antistripping agent; nevertheless, differences between the waxes still existed. For the residual waxes, weatherability was generally positively related to the wax-congealing point. This poses an installation problem in that the low melting waxes are easiest to apply, and soil temperatures may not be hot enough to allow the high congealing point waxes to flow and penetrate the soil. Details of this study will be published in, Residual Wax-Antistripping Agent Mixtures for Water-Harvesting Treatments (in progress).

Work continued on the evaluation of natural plant and animal lipids as soil water-repellents. Several modified tallow and related compounds were evaluated as antistripping compounds for the paraffin treatment, and are now being evaluated as water-repellent soil treatments. Also, studies evaluating candelilla-petroleum-wax mixtures continued. Results showed that wet freeze-thaw cycle weatherability was markedly better for certain mixtures than for candelilla-only treated soil. As with the other wax-soil-treatment-weatherability studies, antistripping agent markedly improved performance. Details will be published in, Weatherability of Candelilla/Petroleum Wax Mixtures (in progress).

Weathering studies have been initiated to evaluate various soil stabilizers to be used in conjunction with water repellent treatments. Stabilizers, potentially, permit a lower repellent application rate, thus should reduce initial installation costs. Furthermore, if erosion is reduced, retreatment and other maintenance cost should be reduced. Stabilizers being evaluated include: cement, cement-plant by-products, lime, various salts, cellulose xanthate, and a number of commercial stabilizers and adhesives.

An erosimeter (Figure 1) was built to increase the water erosive force over that available with the dripolator (see previous Annual Reports for descriptions of the dripolator). Furthermore, since the erosimeter uses a water jet stream which is pressure regulated, a wide range of erosive force is available.

As shown in Figure 1, the petri-dish samples (10 of them) are held in the sample chamber at an angle of 15 degrees - this to facilitate drainage of water away from the point of impingement of the water jet on the treated soil surface. The nozzles are Spraying Sytems Company, $H^{1/8}V$, 0.0003, which produce a 1 mm diameter water jet. The regulator is a Fisher 95L (5 to 15 psi). The nozzle ends are approximately 6-1/2 cm away from the soil surface. The plastic water pipe is adjusted so that the water jets impinge at right angles to and at the exact center of the soil surfaces.

We presently are operating the system at 5 psi, but will be evaluating higher pressures to try shorten sample evaluation time. A study is also underway comparing weathering results from the erosimeter to those from the dripolator.

FIELD STUDIES:

Granite Reef

All catchments and respective treatments are listed in Table 1; respective runoff efficiencies for 1980 are listed in Table 2. Figure 2 is a revised map of the Granite Reef test site. Table 3 is a running list of efficiencies by year for all the wax plots at Granite Reef. Treatment T-6 (slack wax applied in 1973) was removed because of low efficiency. Treatment R-2 (paraffin applied in 1972) was retreated when efficiency dropped below 75%, by hand spreading (as before) chipped paraffin at 0.5 kg/m^2. The original treatment lasted 8 years. The other original wax plot, T-13, which is less subject to erosion, still averaged 90% runoff efficiency in 1980.

An attempt was made to retreat the L-3 silicone plot. A preliminary soil stabilization treatment using cellulose xanthate was unsuccessful because of poor solubilization of the cellulose. Another attempt will be made in 1981.

The liner for the large pond (30 mil nylon reinforced butyl) failed in 1980, after 12 years service. Failure appeared to be due to a dissolving away of the butyl by the paraffin wax, which had been applied for evaporation control in 1973. Since the paraffin cover also had a tendency to submerge and because the wax would not spread to cover the water surface because of low water temperatures, this treatment cannot be recommended for butyl lined- or for pit-water storage units.

Additional information on water-harvesting field treatments appears in the Annual Report Section on "Runoff Farming for Drought-Tolerant Crops for Arid Environments."

SUMMARY AND CONCLUSIONS:

A number of coupling (antistripping) agents was laboratory evaluated for their effect on enhancing the paraffin-soil interfacial bond under freeze-thaw-cycle and water-erosion weathering conditions. All of the antistrips improved weatherability, but there were marked differences among them. Certain of the antistrip-paraffin-mixture treated soils were more than 10 times as resistant to this type weathering compared to the paraffin-only treatment. An effective soil treatement was obtained with only one-half kg/m^2 of paraffin containing 2% antistrip. Stabilization of the soil with cellulose xanthate (made from wastepaper) permitted a further reduction in the application of the paraffin-antistrip mixture to only one-fourth kg/m^2 of soil surface. This is one-eighth the currently recommended rate at field sites on soils subject to natural freeze-thaw cycling.

A number of residual type waxes was laboratory evaluated to compare their freeze-thaw cycle weatherability to that of the paraffin-soil treatment. There were large differences in performance, but in general residual type waxes outperformed refined paraffin. Weatherability of all the waxes was markedly improved by adding an antistripping agent, but differences between the waxes still existed.

One of the two original paraffin-treated water-harvesting plots at the Granite Reef test site (the 200 m^2 plot) was retreated in 1980 (at 0.5 kg/m^2) when runoff efficiency dropped to 63%. This was the eighth complete year since installation. Runoff efficiency for the 200 m^2 plot averaged 81% during that period. The plot harvested 350 cubic meters of water (almost 100,000 gallons, or 5.7 feet of water). Paraffin, at the time of installation, cost 10¢/lb; application rate was 0.68 kg/m^2. The cost of the water, attributable to the material cost of the wax, thus was 30 cents per thousand gallons. The smaller 10 m^2 plot which is less subject to erosion, still averaged 90% runoff efficiency in 1980.

PERSONNEL: Dwayne H. Fink

Table 1. Runoff Plot Treatments at Granite Reef - 1980.

Plot	Size	Date	Treatment
	m^2		
L-1	200	8 Aug 1967	Basecoat, MC-250 at 1.5 kg asphalt m^{-2}.
		22 Aug 1967	Topcoat, RSK asphalt emulsion at 0.7 kg asphalt m^{-2}.
		20 May 1968	Top sheeting, 30-mil chlorinated black polyethylene.
L-2	"	30 Nov 1961	Smoothed soil.
L-3	"	4 Aug 1965	Smoothed soil, treated with 3% solution of sodium methyl silanolate in tap water at 0.06 kg silicone/m^2
		6 Nov 1969	Retreat at 0.04 kg silicone/m^2.
		3 Jun 1975	Retreat at 0.03 kg silicone/m^2.
L-4	"	13 Sep 1976	Polypropylene matting (Mirafi by Celanese) with SS asphalt at 1.4 kg/m^2.
		29 Sep 1976	Sealcoat. Clay emulsion at 0.7 kg/m^2.
		2 Jun 1977	Top spray vinyl aluminum.
L-5	"		Untreated.
L-6	"	15 Jun 1978	Asphalt-fiberglass on N 1/2 area; unwoven polyester fabric (Bitume by Monsanto) - asphalt on S 1/2 area.
L-7	"	3 Aug 1967	Basecoat, MC-250 at 1.5 kg/m^2.
		22 Aug 1967	Topsheeting, 1-mil aluminum foil bonded with RSK asphalt emulsion at 0.7 kg/m^2.
A-1	180	3 Aug 1967	Basecoat, MC-250 at 1.5 kg/m^2.
		22 Aug 1967	Top sheeting, 3/4-oz chopped fiberglass matting bonded with RSK asphalt emulsion at 1.4 kg/m^2.
		Jan 1968	Top spray, vinyl aluminum coating at 0.1 gal/yd^2.
A-2	"	3 Aug 1967	Basecoat, MC-250 at 1.5 kg/m^2.
		12 Sep 1967	Top sheeting, standard rag felt-rock roofing treatment.
A-3	"	1 Aug 1967	Smoothed soil.
A-4	"	10 Nov 1971	Smoothed soil treated with 3% solution of sodium methyl silanolate and 2% soil stabilizer at 1.2 ℓ/m^2
A-5	111.6	Sep 1968	Concrete slab.
R-1	191.1	1 Mar 1965	Ridge and furrow (R&F), 20% side slopes, 3% longitudinal slope, rolled.

Table 1. Runoff Plot Treatments at Granite Reef - 1980 (Cont').

Plot	Size	Date	Treatment
	m^2		
R-2	197.4	29 Sep 1972	R&F, 10% sideslopes, 3% longitudinal, chipped paraffin (128-130 AMP) at 0.68 kg/m^2.
		18 Jun 1980	Retreat, chipped paraffin at 0.5 kg/m^2.
R-3	194.5	1 Mar 1965	R&F, 20% sideslopes.
R-4	208.0	13 May 1966	R&F, 10% sideslopes; 44.9 g/m^2 of sodium carbonate.
		3 Nov 1970	Treated with 3% silicone solution containing 2% soil stabilizer, at 1.2 ℓ/m^2.
		3 Jun 1975	Retreat with 3% silicone solution at 1.2 ℓ/m2, (0.03 kg silicone/m^2 .
W-1	644	1 Dec 1963	Uncleared watershed.
W-2	590	1 Dec 1963	Uncleared watershed.
		3 Jun 1975	Sprayed with 3% silicone solution at 1.2 ℓ/m^2 (0.03 kg silicone/m^2).
W-3	462	1 Dec 1963	Cleared watershed.
		14 Sep 1979	Recleared.
T-1	10	23 Aug 1967	Husky asphalt and Petro mat.
T-2	"		Husky asphalt and gravel.
T-3	"	21 Jun 1979	Sprayed with hot melt of Chevron 140 slack wax containing 5% by wt of Emery 6639 antistripping agent, at 0.5 kg/m^2, to smoothed and compacted soil.
T-4	"	21 Jun 1979	Sprayed with hot melt of Chevron 140 slack wax containing 5% by wt of Emery 6639 antistripping agent, at 0.5 kg/m^2, to plot previously smoothed, compacted, and stabilized with cellulose xanthate (0.5% paper solution applied at 1.6 ℓ/m^2).
T-5	"	12 Sep 1968	Acrylic paint on asphalt.
T-6	"	26 Sep 1973	Slack wax.
		23 Jun 1980	Removed.
T-7	"	19 Sep 1978	Sprayed with hot melt of 128-131 AMP scale paraffin containing 5% (wt) of Emery 6639 antistrip, at 0.5 kg/m^2, to compacted soil. (Treatment identical to those on G.R. Christmas tree catchments).

Table 1. Runoff Plot Treatments at Granite Reef - 1980 (Cont').

Plot	Size	Date	Treatment
	m^2		
T-8	10	15 Apr 1977 23 Jun 1980	Slack wax on fiberglass matting. Removed.
T-9	"	Mar 1968	Hypalon sheeting.
T-10	"	29 Jun 1978	Arizona clay (Superior Co.) at 14 lb/m^2 and stock salt at 2.5 lb/m^2 rototilled into top 2-inch soil, and compacted with vibratory roller following 2-inch rain of 26 July (10% "clay" in top 2-inch and 5 T salt/acre).
T-11	"	21 May 1968	Butyl sheeting (10 mil).
T-12	"	17 Jul 1979	Sprayed hot melt of Chevron 140 slack wax containing 5% by wt of Emery 6639 antistrip, at 0.6 kg/m^2, to plot previously smoothed, compacted and stabilized with cellulose xanthate (0.5% solution at 3.2 ℓ/m^2).
T-13	"	29 Jun 1972	Chipped paraffin (143-150 AMP), at 0.73 kg/m^2.
T-14	"	Jul 1972	Smoothed.
T-15	"	10 Jul 1979	Sprayed with hot melt of 128-130 AMP scale wax containing 5% (wt) Emery 6639 antistrip, at 0.6 kg/m^2 to smoothed and stabilized plot (0.25% (wt) paper solution at 3.2 ℓ/m^2).

Table 2. Rainfall-runoff from water harvesting plots at Granite Reef in 1980.

Date	Precip.	L-1	L-2	L-3	L-4	L-5	L-6	L-7	R-1	R-2	R-3	R-4	A-1	A-2	A-3	A-4	A-5
1980	mm								%								
9-10 Jan	16.3	89.5	0	22.7	87.0	UN	M	64.1	M	63.3	M	16.3	M	44.9	1.9	14.6	91.7
10-11	11.9	85.9	0	28.1	73.1	UN	93.2	58.5	M	57.4	M	19.1	M	35.1	3.8	21.1	85.4
19-20	15.5	87.7	0	45.9	72.8	UN	94.7	61.2	23.7	61.2	5.5	31.8	95.7	37.6	11.0	39.4	86.0
21	12.2	86.0	0	48.8	89.1	UN	98.0	72.8	17.3	66.6	8.8	33.1	90.8	51.9	16.0	39.5	84.2
29-30	13.5	89.3	27.0	35.4	89.6	UN	99.3	60.7	0.4	56.4	0	19.3	96.3	43.7	3.2	29.0	90.6
13-14 Feb	16.2	91.4	22.4	39.2	92.7	UN	101.7	62.2	3.6	32.5	3.8	12.0	99.0	46.0	2.1	25.8	91.0
14-15	32.2	95.5	25.8	73.6	92.9	UN	104.2	80.9	33.1	79.1	32.2	58.8	92.1	71.2	39.2	63.2	88.3
16-18	36.6	85.2	28.9	65.4	79.7	UN	86.5	75.2	36.6	75.3	36.2	52.9	96.3	59.5	43.7	55.4	88.0
19-20	18.8	96.8	?	90.0	94.4	UN	99.8	89.9	63.8	87.4	53.8	74.2	95.5	81.2	58.7	75.0	87.3
20-21	6.1	83.0	1.5	18.9	83.0	UN	89.1	37.0	9.6	42.6	5.7	5.0	91.8	28.1	1.2	11.0	88.1
3 Mar	5.6	96.0	0	29.6	?	UN	97.0	57.2	0	12.8	0	17.6	97.0	39.1	0	18.4	88.2
10-11	17.0	89.9	32.9	62.0	88.3	UN	96.1	71.1	38.6	58.2	33.8	49.1	92.6	61.9	39.8	50.4	90.4
19	6.1	89.3	0	16.1	89.9	UN	94.5	44.3	0	51.3	0	6.5	91.9	28.9	0	10.1	90.5
26	1.5	89.3	0	0	37.0	UN	97.3	19.0	0	20.9	0	0	97.8	0	0	0	81.2
1 Apr	8.1	86.2	0	25.4	87.4	UN	92.7	55.2	0	56.6	0	10.1	89.7	39.2	0	12.3	83.5
29-30	10.7	85.4	0	7.5	83.6	UN	87.1	53.8	0	60.4*	0	9.7	86.6	30.4	0	9.4	84.8
30 Jun	6.8	92.6	0	6.7	87.6	UN	97.0	37.6	0	84.2	0	0	79.3	17.6	0	2.4	64.2
13 July	8.9	92.7	0	37.1	95.9	UN	106.1	79.2	0	99.4	0	32.2	94.1	45.8	4.6	36.0	75.5
25	11.9	92.1	9.2	52.3	87.0	UN	102.2	79.0	36.0	102.0	21.5	29.6	90.1	?	11.0	34.3	69.1
3 Aug	7.1	NP															
9	2.0	NP															
13	4.6	NP															
24	3.6	NP															
5 Sep	14.7	NP															
11	5.1	88.4	0	22.1	74.8	UN	92.8	55.3	13.7	85.4	8.1	22.5	77.8	9.9	0	29.1	M
Totals**	293.0	89.8	13.4	47.6	86.0	UN	96.4	67.5	24.0	63.5 95.0	19.5	34.5	93.0	48.0	20.5	38.5	86.0

Notation: F = Overflowed storage; M = Mechanical malfunction; UN = Untreated; NP = Not pumped (data from tipping bucket raingage)
? = Questionable data.

* = Initation of new treatment or maintenance of catchment.

** = Percentage totals are based on measured data only, i.e., no estimates.

Table 2. Rainfall-runoff from water harvesting plots at Granite Reef in 1980 (continued).

Date	Precip.	W-1	W-2	W-3	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12	T-13	T-14	T-15
1980	mm	%																	
9-10 Jan	16.3	↓	↓	↓	114.1	85.9	84.0	81.0	106.7	19.0	86.5	26.4	50.3	27.6	111.6	108.0	96.3	9.2	106.1
10-11	11.9	8.1	7.5	15.0	106.7	84.9	79.0	81.5	93.3	31.1	88.2	33.6	74.8	36.1	104.2	103.4	86.6	0	96.6
19-20	15.5	10.5	9.5	18.2	104.5	80.6	87.1	M	M	43.2	92.3	47.7	85.2	47.1	105.2	99.3	85.8	24.5	98.7
21	12.2	12.8	31.1	23.6	102.4	93.4	79.5	90.2	95.1	44.3	96.7	50.0	96.7	54.1	100.8	95.1	86.9	30.3	97.5
29-30	13.5	8.0	9.0	14.5	97.0	98.5	96.3	101.5	100.7	34.8	98.5	45.2	M	43.7	105.9	105.9	87.4	17.0	100.7
13-14 Feb	16.2	7.9	9.4	13.2	95.1	?	98.1	?	98.8	?	95.7	?	110.5	?	?	104.9	85.8	11.7	100.0
14-15	32.2	↓	↓	↓	104.6	91.6	99.7	102.5	95.6	75.8	99.1	?	?	?	?	?	97.2	52.8	100.6
16-18	36.6	32.4	↓	30.7	F	F	F	F	F	M	F	M	F	M	F	F	F	M	F
19-20	18.8	44.3	↓	↓	103.2	92.0	100.5	97.9	95.7	38.8	97.9	73.9	98.4	80.8	104.8	102.6	96.8	65.4	96.8
20-21	6.1	0	20.5	52.2	101.6	85.2	90.2	96.7	91.8	16.4	73.8	29.5	104.9	18.0	104.9	100.0	88.5	9.8	95.1
3 Mar	5.6	0	0	0	100.0	85.7	91.1	78.6	105.4	21.4	92.8	39.3	105.4	17.8	105.4	100.0	91.1	7.1	85.7
10-11	17.0	37.0	33.1	35.6	103.5	91.2	94.1	98.8	100.6	58.2	98.2	64.7	97.0	60.0	104.7	101.8	96.5	44.7	101.2
19	6.1	0	0	0	106.6	80.3	88.5	101.6	96.7	19.7	90.2	42.6	113.1	18.0	114.8	104.9	86.9	9.8	103.3
26	1.5	0	0	0	66.7	13.3	M	13.3	20.0	0	40.0	0	100.0	0	100.0	80.0	0	0	46.7
1 Apr	8.1	5.8	12.1	10.6	96.3	65.4	86.4	91.4	87.6	14.8	88.9	37.0	97.5	21.0	98.8	?	82.7	6.2	96.3
29-30	10.7	8.5	8.7	8.0	95.3	71.0	84.1	85.0	86.9	21.5*	90.6	27.1*	99.1	19.6	102.8	92.5	87.8	17.7	94.4
30 Jun	6.8	0	0	0	108.8	55.9	72.0	63.2	73.5	UN	66.2	UN	102.9	11.8	105.9	73.5	85.3	5.9	80.9
13 July	8.9	0	0	0	NP														
25	11.9	8.6	12.0	17.2	?	81.5	88.2	75.6	84.9	UN	?	UN	91.6	53.8	101.0	78.2	90.8	10.1	90.8
3 Aug	7.1	NP																	
9	2.0	NP																	
13	4.6	NP																	
24	3.6	NP																	
5 Sep	14.7	NP																	
11	5.1	0	0	0	M	45.1	56.9	54.9	M	UN	68.6	UN	105.9	33.3	90.2	17.7	74.5	15.7	M
Totals**	293.0	17.6	13.8	21.7	102.7	84.4	90.3	90.3 (89.8)	95.3	42.7	92.4	45.9	93.3	42.1	100.1	98.4	90.3	26.3	98.0

Notation: F = Overflowed storage; M = Mechanical malfunction; UN = Untreated; NP = Not pumped (data from tipping-bucket raingage);
↓ = Accumulated events; ? = Questionable data.
* = Initation of new treatments or maintenance of catchment.
** = Percentage totals are based on measured data only; i.e., no estimates.

Table 3. Summary of runoff efficiencies from wax-treated plots at Granite Reef.

		Wax-Treated Plots 1/							
Year	Precip. mm	R-2	T-13	T-6	T-7	T-3	T-4	T-12	T-15
		% runoff							
1972	244	90	92						
1973	208	87	88						
1974	251	85	2/	75					
1975	183	88	96	76					
1976	193	86	91	73					
1977	116	70	77	53					
1978	540	81	88	62	83				
1979	242	76	89	52	88	63	87	93	90
1980	293	63/95 3/	90	43/ 4/	92	90	90	98	98

1/ First year's data represents partial year.

2/ Missing data.

3/ Retreated during year.

4/ Terminated during year.

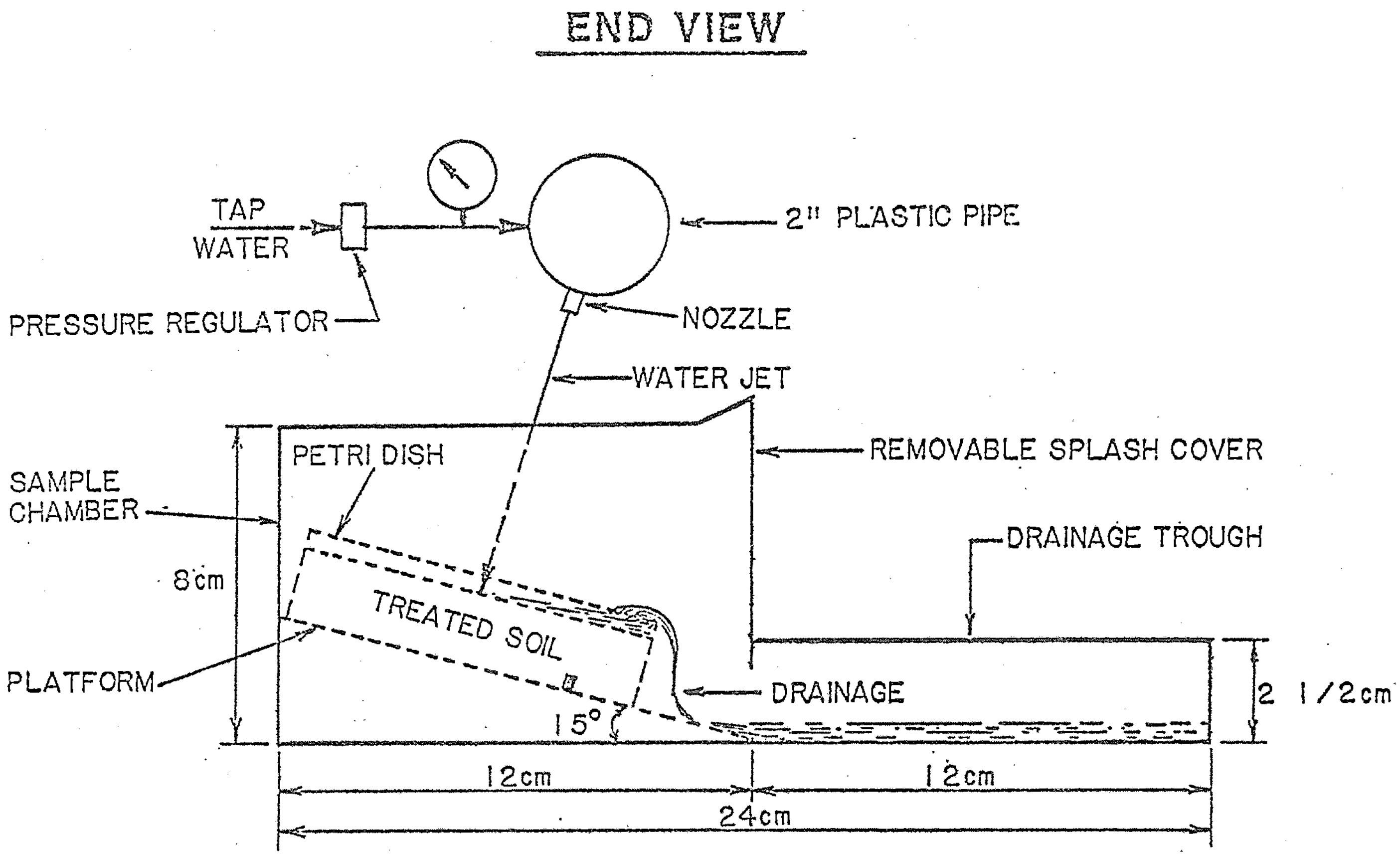

Figure 1. Erosimeter for soil structural evaluation.

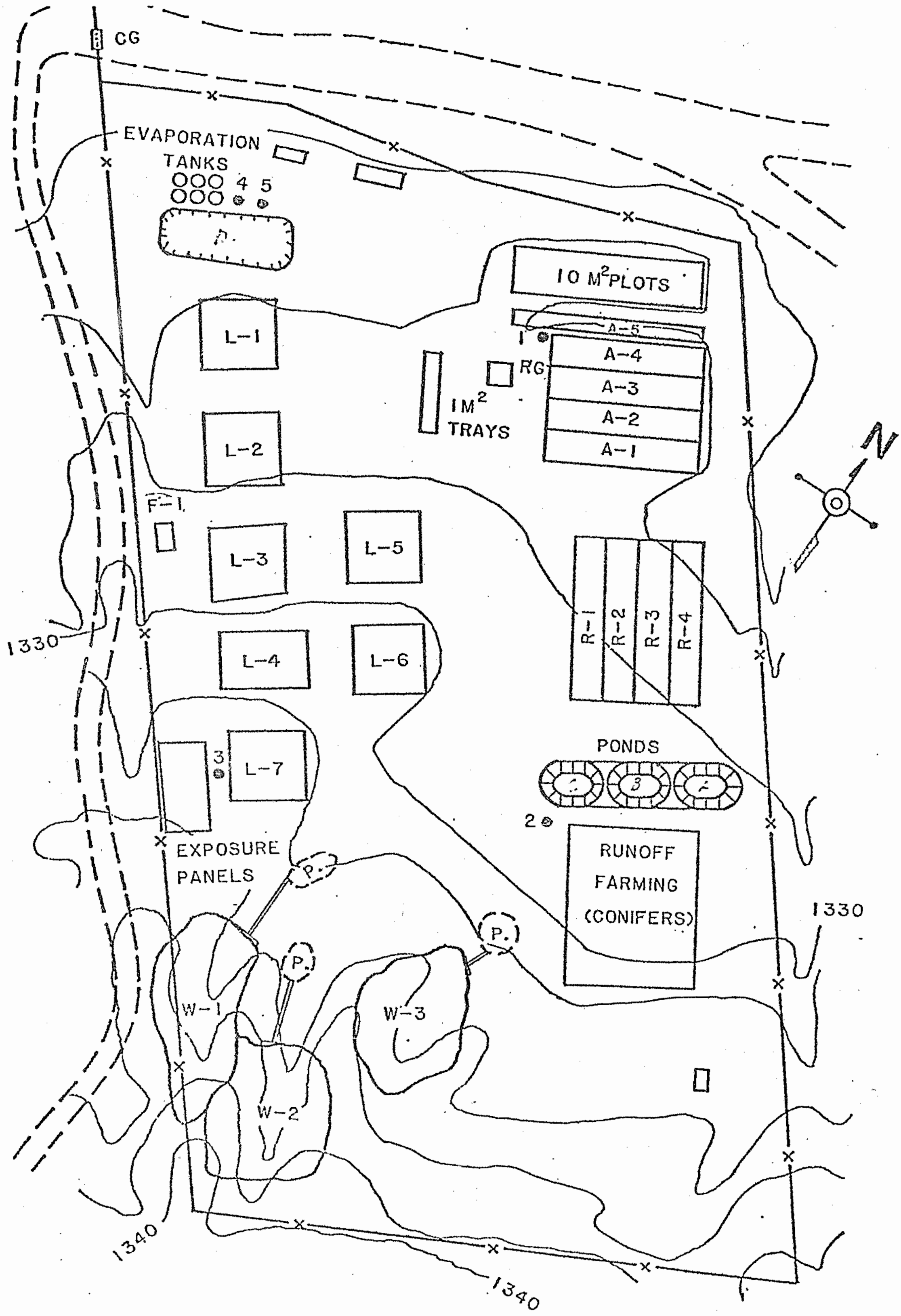

Figure 2. Diagram of Granite Reef Water Harvesting site.

APPENDIX

LIST OF PUBLICATIONS

AND MANUSCRIPTS PREPARED IN 1980

		MS No.
NRP 20740	IMPROVE IRRIGATION AND DRAINAGE OF AGRICULTURAL LAND	
Published:		
	Bucks, D. A., French, O. F. and Nakayama, F. S. 1980. Drip water management for selected vegetable and vineyard crops. In Proc. of the Symposium on Drip Irrigation in Horticulture with Foreign Experts Participating. (Sept. 30-Oct. 4, 1980) Skierniewice, Poland. p. 89.	807
	Bucks, D. A. and Nakayama, F. S. 1980. Injection of fertilizers and other chemicals for drip irrigation. In Proc. Irrigation Assoc., First Agri-Turf Irrigation Exposition and Irrigation Technical Conference, Houston, TX. 25-27 Feb. 1980, "Total Irrigation--Show and Tell." pp. 166-180.	759
	Clemmens, A. J. and Replogle, J. A. 1980. Constructing simple measuring flumes for irrigation canals. USDA Farmers Bulletin No. 2268.	695
	Clemmens, A. J. 1980. Depths of flow in level basins. Trans. Am. Soc. of Agr. Engin. 23(4):910-913.	715
	Clemmens, A. J. 1979. Verification of the zero-inertia model for border irrigation. Trans. Am. Soc. of Agr. Engin. 22(6):1306-1309.	670
	Dedrick, A. R. 1980. The history of butyl rubber membranes for water conservation in agriculture. In Proc. of Henry C. Remsberg Memorial Education Symp. Am. Chem. Soc. Rubber Div., Las Vegas, NV. pp. II-1 to II-14.	787
	Dedrick, A. R. 1980. Land leveling-precision attained with laser controlled drag scrapers. 1979 Winter Meeting, Am. Soc. Agr. Engin., 11-14 Dec. 1979. New Orleans, LA.	767

MS. No.

Dedrick, A. R. 1980. Level-basin irrigation --automation. In Proc. Irrigation Assoc., First Agri-Turf Irrigation Exposition and Irrigation Technical Conference, Houston, TX. 25-27 Feb. 1980, "Total Irrigation -- Show and Tell." pp. 86-99. 750

Erie, L. J. and Dedrick, A. R. 1980. Level basin irrigation leads to higher yields. California-Arizona Farm Press. 27 Oct. p.16. 757

Howell, T. A., Bucks, D. A., and Chesness, J. L. 1980. Advances in trickle irrigation. Proc. of the Am. Soc. of Agr. Engin. Second National Irrigation Symp., 20-23 Oct., 1980. Lincoln, NE. "Irrigation Challenges of the 80's." pp. 69-94. 821

Nakayama, F. S., Bucks, D. A. and Gilbert, R. G. 1980. Drip emitter clogging problems and solutions. Summary In Proc. of the Symp. on Drip Irrigation in Horticulture with Foreign Experts Participating. Skierniewice, Poland. p. 209. 808

Replogle, J. A. and Clemmens, A. J. 1979. Broadcrested weirs for portable flow metering. Trans. Am. Soc. Agr. Engin. 22(6):1324-1328. 681

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Riekert, H., Swindel, B. F. and Replogle, J. A. 1980. Effect of forestry practices in Florida watersheds. In Proc. of Symp. on Watershed Management, Am. Soc. Civil Engin., Boise, ID. 21-23 July 1980. pp. 706-720. 814

MS No.

Prepared: Bucks, D. A., Nakayama, F. S. and French, O. F. Keys to successful trickle irrigation: Management and maintenance. In Proc. Agri. Plastics Assoc. 15th NAPA Congress. (Submitted for publication) 777

Bucks, D. A., Erie, L. J., French, O. F., Nakayama, F. S. and Pew, W. D. Subsurface trickle irrigation management using multiple cropping practices. Trans. Am. Soc. Agr. Engin. (Submitted for publication) 806

Clemmens, A. J. and Dedrick, A. R. Estimating distribution uniformity in level basins. Trans. Am. Soc. of Agr. Engin. (In press) 788

Clemmens, A. J. Evaluation of infiltration measurements for border irrigation. Agric. Water Management. (In press) 793

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Gilbert, R. G., Nakayama, F. S., Bucks, D. A., French, O. F., Adamson, K. and Johnson, R. M. Trickle irrigation: Predominant bacteria in treated Colorado River water and biologically clogged emitters. Agricultural Water Management. (Approved for publication) 785

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Replogle, J. A. Advances in irrigation technology -- On farm irrigation practices. Proc. of the Agricultural Sector Symposia, organized by the Agriculture and Rural Development and Personnel Management Departments, World Bank, Washington, D. C. (Approved for publication) 810

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NRP 20760 MANAGEMENT AND USE OF PRECIPITATION AND SOLAR ENERGY FOR CROP PRODUCTION

Published: Allen, R. F., Jackson, R. D. and Pinter, P. J., Jr. 1980. To relate Landsat data to U.S. agriculture. Agricultural Engineering. 61(11):12-14. 732

Hatfield, J. L., Millard, J. P., Reginato, R. J., Jackson, R. D., Idso, S. B., Pinter, P. J., Jr. and Goettelman, R. C. 1980. Spatial variability of surface temperature as related to cropping practice with implications for irrigation management. Proc. of the 14th Annual Symp. on Remote Sensing of Environment. pp. 1311-1320. 763

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Prepared: Ehrler, W. L. and Bucks, D. A. Soil water depletion in irrigated guayule. Proc. 3rd Intern. Conf. on Guayule. Pasadena, CA. April 27-May 1, 1980. (Approved for publication) 772

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Jackson, R. D., Jones, C. A., Uehara, G. and Santos, L. T. Remote detection of nutrient and water deficiencies in sugarcane under variable cloudiness. Remote Sensing of Environment. (Approved for publication) 802

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Kimball, B. A., Idso, S. B. and Aase, J. K. A model of thermal radiation from cloudy skies. J. Geophysical Research, Oceans and Atmosphere Section. 813

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Paluska, M. M. and Ramage, R. T. The morphology of barley spikes selected from a male sterile facilitated recurrent selection population for awn variation. Crop Science. (Submitted for publication) 809

NRP 20790 PREVENTING POLLUTION OF AND IMPROVING THE QUALITY OF SOIL, WATER, AND AIR

Published: Bouwer, H. 1980. Basic groundwater aspects (over-view address). In Water Resources in Arizona's Future. Proc. of the Eighth Annual Summer Conf., Governor's Commission on Arizona Environment. Melvin G. Marcus (Ed.). 14-17, Aug. pp. 19-26. 779

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	Lance, J. C., Rice, R. C. and Gilbert, R. G. 1980. Renovation of sewage water by soil columns flooded with primary effluent. J. Water Pollution Control Fed. 52(2):381-388.	697
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	Bouwer, H. Cylinder infiltrometers. In Monograph on Methods of Soil Analysis. Am. Soc. of Agron. (In press)	790
	Bouwer, H. and Rice, R. C. The Flushing Meadows project -- Wastewater renovation by high-rate infiltration for groundwater recharge. In Proc. Intnl. Conf. on Cooperative Research Needs for the Renovation and Reuse of Municipal Wastewater in Agriculture. 15-19 Dec. Mexico City, Mex. (In press)	799
	Bouwer, H. Wastewater reuse in arid areas. In Water Reuse. E. J. Middlebrooks (Ed.), Ann Arbor Science Publishers, Inc. (In press)	789
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Lance, J. C. and Gerba, C. P. Virus removal with land filtration. In Water Reuse. E. J. Middlebrooks (Ed.), Ann Arbor Science Publishers, Inc. (In press) 774

NRP 20810 CONSERVE AND MANAGE AGRICULTURAL WATER

Published: Cooley, K. R. and Idso, S. B. 1980. Effects of lily pads on evaporation. Water Res. Res. 16(3):605-606. June 1980. 741

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